Stream temperature dynamics following riparian wildfire: Effects of stream-subsurface interactions and standing dead trees

by

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Abstract

The primary objectives of this study were to address how stream temperature is influenced by (1) spatial variability in energy exchanges, (2) reach-scale stream-subsurface water interactions and (3) the net radiation dynamics associated with standing dead riparian vegetation. Stream temperature, riparian microclimate, and hydrology were characterized for a 1.5 km reach of Fishtrap Creek, located north of Kamloops, British Columbia. Within-reach air temperature and humidity variability was small, while wind speed, net radiation and surface-subsurface interactions exhibited considerable spatial variability. The field data were used to drive a deterministic energy budget model to predict stream temperature. The model was evaluated against measured stream temperature and performed well. The model indicated that the spatially complex hydrology was a significant control on the observed stream temperature patterns. A modelling exercise using three canopy cover scenarios revealed that post-disturbance standing dead trees reduce daytime net radiation reaching the stream surface by one third compared to complete vegetation removal. However, standing dead trees doubled daytime net radiation reaching the stream compared to pre-wildfire conditions.

The results of this study have highlighted the need to account for the spatial variability of energy exchange processes, specifically net radiation and surface-subsurface water interactions, when understanding and predicting stream thermal regimes.
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Chapter 1

Introduction

1.1 Motivation for the study

Stream temperature is a principal determinant of aquatic ecosystem composition and productivity. It controls the solubility of oxygen, rates of biochemical and biological processes, and can influence the distribution of aquatic organisms within the stream environment (Beschta et al., 1987). Land use and water management can modify stream temperature regimes, with potentially deleterious effects on stream ecology, and these effects have received significant attention in the literature (Moore et al., 2005a; Caissie, 2006).

There is increasing concern about the effects of climate change on stream temperature (Caissie, 2006). Climate change could modify several of the factors that control stream temperature (Figure ??). Direct effects of climate warming include increased incident longwave radiation and sensible heat transfer from the atmosphere. In addition, it is reasonable to expect groundwater temperatures to increase (Meisner et al., 1988). Indirect effects include changes in streamflow (e.g., due to earlier seasonal snowmelt, glacier retreat, changes in summer rainfall) and riparian vegetation (e.g., due to changes in climatic suitability for different vegetation communities or increased frequency of forest fires). Most previous studies have used correlations between stream and air temperature, coupled with projected changes in air temperature based on general circulation models, to estimate the effects of climatic warming (e.g. Eaton and Scheller 1996; Mohseni et al. 2003). One notable exception is the study by Gooseff et al. (2005) who used an energy balance model to estimate effects of climatic warming on stream temperature.

The most rigorous basis for understanding and predicting the effects
of environmental change on stream temperature is through understanding the energy and water budgets at scales ranging from a point, stream reach and ultimately to an entire stream network. The overall objective of this study was to contribute to our understanding of the physical controls on stream temperature at the reach scale. In addition, the thesis research was conducted at a study site recently disturbed by a wildfire. The wildfire disturbance provided an opportunity to address how the change in riparian vegetation structure due to the wildfire affected reach scale stream temperature patterns. The remainder of this chapter consists of a literature review (Section 1.2) to provide the context for the specific research questions, which are outlined in Section 1.3.

1.2 Literature review

1.2.1 Physical controls on stream temperature

Stream temperatures reflect the influences of a variety of energy fluxes. These energy fluxes include solar radiation, longwave radiation, sensible heat, latent heat, bed heat conduction, heat from groundwater discharge, and hyporheic heat exchanges. Many of the fluxes are related to riparian zone properties, such as riparian vegetation, which provides shade, emits longwave radiation and influences turbulent exchange. The processes will vary in space due to heterogeneity of riparian zone and stream characteristics over the distance of a stream reach. The processes will vary in time due to changes in riparian zone and stream characteristics over time (e.g. riparian disturbances) and temporal variability in energy availability over diurnal, synoptic, seasonal and longer time scales. Better understanding of the spatiotemporal variability in energy exchange processes will allow improved prediction of stream temperature response to environmental change.

The energy budget framework has been used to understand stream temperature dynamics and their physical controls in a variety of settings. The following review will present, with special reference to spatiotemporal variability, the previous approaches and assumptions used to characterize (1) the
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atmosphere-stream surface energy exchanges and (2) the energy exchanges associated with hydrological processes.

Many energy budget studies have modelled stream temperature using data from meteorological stations located up to 300 km from the study stream (e.g. Sinokrot and Stefan 1993; Bogan et al. 2004; Sridhar et al. 2004; Caissie et al. 2007). Significant microclimate gradients for variables such as air temperature and humidity have been found to exist as close as 30 m from the stream (Brosofske et al., 1997). Therefore, remote meteorological data may not represent conditions above the stream, and many studies have used calibration parameters to adjust the computed energy exchanges (e.g. Bogan et al. 2004; Caissie et al. 2007). There have been approximately a dozen energy budget studies that have used meteorological measurements above the stream surface or measured within 100 m of the stream to estimate energy budget components. These studies are summarized in Table 1.1 and will be the focus of the remaining review.

Of the various energy exchange, net radiation is often cited as the most important stream temperature control (Brown, 1969; Evans et al., 1998; Webb and Zhang, 1999; Hannah et al., 2008). Net radiation has been measured using a net radiometer (Brown, 1969) or has been calculated using the Stefan-Boltzmann law for longwave radiation in conjunction with pyranometer measurements of shortwave radiation (Evans et al., 1998). These measurements have usually been made at only one location along the stream reach and have thus ignored the spatial variability of net radiation. Moore et al. (2005b) and Guenther (2007) accounted for spatial variability in riparian vegetation structure by developing a net radiation model using the spatial distribution of gap fractions from hemispherical photographs.

Latent and sensible heat fluxes have been found to be secondary terms compared to net radiation. Latent and sensible heat fluxes have been typically determined using Penman-type equations and the Bowen ratio. Webb and Zhang (1997) found that a Penman-type equation for the latent heat flux agreed well with measured pan evaporation. Guenther (2007) further confirmed the Penman-type equation using evaporimeters submerged in the stream.
Chapter 1. Introduction

While Moore et al. (2005b) and Guenther (2007) accounted for spatial variability in net radiation, there has been little attention to within-reach variability of the other energy exchange processes. In particular, the measurements to estimate the turbulent exchanges have been made at one location along the stream, with no consideration of how representative these measurements are for a longer reach. While within-reach variability in atmosphere-stream surface energy exchanges has not been explicitly addressed, temporal and between-reach spatial variability has. Hannah et al. (2008) examined the temporal variability in riparian microclimate for two stream reaches located in Scotland and found strong diurnal and seasonal patterns in the microclimatic parameters measured. Webb and Zhang (1997) examined the spatial variability in riparian microclimate between eleven different stream reaches in the Exe Basin, Devon, UK. They found that riparian microclimates for the various reaches varied widely depending on the local characteristics of the stream channel (e.g. channel morphology, riparian vegetation and valley topography) and on the prevailing weather conditions during the period of study. The high degree of between-reach spatial variability and temporal variability in atmospheric-stream surface fluxes suggests that within-reach variability should also be addressed.

The focus of nearly all previous energy budget studies has been on the vertical energy exchanges occurring at the air/water interface. Hydrological processes such as groundwater-surface water interactions can significantly influence stream temperature patterns (Malard et al., 2001; Brown et al., 2005). However, few studies have incorporated detailed hydrological measurements within an energy budget framework to understand stream temperature patterns. The groundwater influence on the stream thermal regime has typically been assumed to be negligible, or has been measured by subtracting measurements of downstream discharge from upstream discharge (Table 1.1). Other approaches have included the assumption that groundwater contributions were proportional to drainage area (Moore et al., 2005b) and the use of stream temperatures to infer groundwater processes (Hannah et al., 2008). The advective flux associated with groundwater discharging into the stream has generally been considered a relatively minor term compared to
net radiation (Webb and Zhang, 1999; Hannah et al., 2008), which may be partially due to a failure in accurately quantifying this flux.

In contrast to most energy budget research, Story et al. (2003) coupled the energy budget approach with detailed hydrological measurements to quantify the role of surface-subsurface water interactions on stream temperature. Story et al. (2003) augmented discharge measurements with tracer and piezometer measurements in order to characterize groundwater and hyporheic contributions. They found that simply comparing upstream and downstream discharge did not reveal the complex hydrology that was responsible for the observed stream temperature patterns. The spatiotemporal dynamics of the groundwater and hyporheic exchanges were important in driving observed downstream cooling. The work by Story et al. (2003), Malard et al. (2001), and Brown et al. (2005) shows that streams can have complex hydrology which strongly influences the thermal regime. Coupling the energy budget and water budget approaches at different scales will further our understanding of, and our ability to predict, stream temperature patterns.

1.2.2 Stream temperature response to wildfire

There appear to have been only seven published studies on the effect of wildfire disturbances on stream temperature (Table 1.2). This paucity of studies is likely due to the unpredictable nature of wildfire occurrence, therefore making planned wildfire research difficult. All studies showed an increase in stream temperature following the wildfire disturbance. However, the estimated magnitude of warming may be confounded by natural variability between the thermal regimes of disturbed and control streams and/or the failure of a single stream temperature monitoring point to represent a reach-scale response (Leach and Moore, in press).

Only two studies have attempted to relate the observed stream warming following the wildfire to changes in physical processes. Amaranthus et al. (1989) found that post-wildfire daily maximum stream temperatures were highly variable and not strongly correlated with measured stream shade.
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<table>
<thead>
<tr>
<th>Site (Reference)</th>
<th>Stream (m)</th>
<th>Reach length (m)</th>
<th>Riparian structure</th>
<th>Net radiation structure</th>
<th>Net radiation</th>
<th>Groundwater</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Oregon (Brown, 1969)</td>
<td>Deer Creek</td>
<td>427</td>
<td>Heavily shaded coniferous forest</td>
<td>Single net radiometer</td>
<td>Negligible</td>
<td>Assumed negligible</td>
<td>Qs - Qs</td>
</tr>
<tr>
<td>Berry Creek</td>
<td>HJ Andrews</td>
<td>396</td>
<td>Clear cut</td>
<td>Single net radiometer</td>
<td>Negligible</td>
<td>Assumed negligible</td>
<td>Qs - Qs</td>
</tr>
<tr>
<td>Long Island, NY (Phleger et al., 2013)</td>
<td>Connetquot</td>
<td>1500</td>
<td>Urban</td>
<td>Three net radiometers and one net radiometer</td>
<td>Negligible</td>
<td>Not determined</td>
<td>Qs - Qs</td>
</tr>
<tr>
<td>Italy (Vugts, 1974)</td>
<td>Vigliach</td>
<td>9000</td>
<td>Partially wooded</td>
<td>Single net radiometer and shade meter</td>
<td>Negligible</td>
<td>Assumed negligible</td>
<td>Qs - Qs</td>
</tr>
<tr>
<td>Exe Basin, UK (Vugts, 1974)</td>
<td>Eleven streams</td>
<td>24-36</td>
<td>Pasture and woodland</td>
<td>Single net radiometer</td>
<td>Negligible</td>
<td>Assumed negligible</td>
<td>Qs - Qs</td>
</tr>
<tr>
<td>Devon, UK (New and Zhang, 1997)</td>
<td>River Tavy</td>
<td>40</td>
<td>Pasture</td>
<td>Single net radiometer</td>
<td>Negligible</td>
<td>Assumed negligible</td>
<td>Qs - Qs</td>
</tr>
<tr>
<td>North-central BC</td>
<td>River Bere</td>
<td>B5</td>
<td>Forested</td>
<td>Single net radiometer</td>
<td>Negligible</td>
<td>Assumed negligible</td>
<td>Qs - Qs</td>
</tr>
<tr>
<td>HJ Andrews, (Evans et al., 1998)</td>
<td>WS 3 bedrock</td>
<td>200</td>
<td>Pasture corrected for bank shading</td>
<td>Single net radiometer</td>
<td>Negligible</td>
<td>Assumed negligible</td>
<td>Qs - Qs</td>
</tr>
<tr>
<td>Staffordshire, UK (Evans et al., 1998)</td>
<td>River Blithe</td>
<td>25</td>
<td>Pasture</td>
<td>Single net radiometer</td>
<td>Negligible</td>
<td>Assumed negligible</td>
<td>Qs - Qs</td>
</tr>
<tr>
<td>Dorset, UK (Evans et al., 1998)</td>
<td>River Bere</td>
<td>200</td>
<td>Pasture</td>
<td>Single net radiometer and S-B equation</td>
<td>Negligible</td>
<td>Assumed negligible</td>
<td>Qs - Qs</td>
</tr>
<tr>
<td>Devon, UK (Story et al., 2003)</td>
<td>WS 3 alluvial</td>
<td>200</td>
<td>Pasture and shade meter</td>
<td>Single net radiometer</td>
<td>Negligible</td>
<td>Assumed negligible</td>
<td>Qs - Qs</td>
</tr>
<tr>
<td>Taylor Valley, Antarctica (Cozzetto et al., 2006)</td>
<td>Von Guerard</td>
<td>143</td>
<td>No vegetation</td>
<td>Single net radiometer</td>
<td>Negligible</td>
<td>Assumed negligible</td>
<td>Qs - Qs</td>
</tr>
<tr>
<td>Malcolm Knapp, BC Griffith Creek (Moore et al., 2005a)</td>
<td>Griffith Creek US</td>
<td>20</td>
<td>Moorland</td>
<td>Spatial model using hemispherical images and S-B equation</td>
<td>Negligible</td>
<td>Assumed proportional</td>
<td>Qs - Qs</td>
</tr>
<tr>
<td>South Island, BC Griffith Creek (Guenther, 2007)</td>
<td>Griffith Creek Med</td>
<td>20</td>
<td>Moorland</td>
<td>Spatial model using hemispherical images and S-B equation</td>
<td>Negligible</td>
<td>Assumed proportional</td>
<td>Qs - Qs</td>
</tr>
<tr>
<td>Taylor Valley, Antarctica (Cozzetto et al., 2006)</td>
<td>Von Guerard</td>
<td>143</td>
<td>No vegetation</td>
<td>Single net radiometer and pyranometer</td>
<td>Negligible</td>
<td>Assumed proportional</td>
<td>Qs - Qs</td>
</tr>
<tr>
<td>Glen Girnock, UK (Guenther, 2007)</td>
<td>Griffith Creek Med</td>
<td>20</td>
<td>Moorland</td>
<td>Spatial model using hemispherical images and S-B equation</td>
<td>Negligible</td>
<td>Assumed proportional</td>
<td>Qs - Qs</td>
</tr>
<tr>
<td>Glen Girnock, UK (Guenther, 2007)</td>
<td>Griffith Creek Med</td>
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<td>Negligible</td>
<td>Assumed proportional</td>
<td>Qs - Qs</td>
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</tbody>
</table>

Emissivity of longwave radiation calculated using Stefan-Boltzmann (S-B) law.
Their results suggest that either shade was poorly quantified, shade was a poor surrogate for quantifying radiation fluxes, or other processes may have been controlling the stream temperature regime. In a retrospective study of nine streams with varying degrees of wildfire history, Dunham et al. (2007) found that recently burned streams with considerable channel morphology response were more likely to have daily maximum stream temperatures exceed 20 °C than burned or unburned streams. Their study implies relationships between increased insolation and disturbances of the riparian vegetation and channel morphology; however, they do not directly quantify or address the actual physical processes response for the stream temperature patterns.

This lack of attention to physical processes controlling the magnitude and pattern of stream temperature response to riparian wildfire makes it difficult to extrapolate the observed temperature responses to other streams. The role of undisturbed riparian vegetation in moderating stream temperature, particularly in a forest management context, is well known (Moore et al., 2005a). However, it is unclear what effect standing dead riparian trees have on radiation and turbulent energy exchanges.

Understanding the effect of standing dead trees on energy exchange processes and stream temperature would be valuable for two primary reasons. First, emulating wildfire disturbances is seen as an important forest management approach for achieving ecologically sustainable silviculture (Nitschke, 2005). Therefore, understanding the effect of wildfire disturbances is essential in providing the guidance for sustainable forest management practices. Second, following wildfire there is often pressure to salvage harvest the disturbed areas (Donato et al., 2006). Therefore, it would be valuable to understand how standing dead trees differ, with regards to energy exchange processes and stream temperature, from both undisturbed forest and salvage harvesting (i.e., complete removal of vegetation). It is unknown to what degree standing dead trees provide shade and whether they should be left unharvested to moderate stream warming due to insolation.
Table 1.2: Summary of previous studies of stream temperature response to wildfire disturbance.

<table>
<thead>
<tr>
<th>Study Site (Reference)</th>
<th>Catchment</th>
<th>Catchment Size (ha)</th>
<th>Wildfire Extent (% Burned)</th>
<th>Temperature Variable</th>
<th>Methodology</th>
<th>Temperature Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Central</td>
<td>Fox</td>
<td>473</td>
<td>100%</td>
<td>Summer</td>
<td>Before-after</td>
<td>Spring: ↑ 2°C</td>
</tr>
<tr>
<td>Washington (Helvey, 1972)</td>
<td>Burns</td>
<td>564</td>
<td>100%</td>
<td>daily max</td>
<td>with control</td>
<td>Summer: ↑ 6°C</td>
</tr>
<tr>
<td>Northwest</td>
<td>Deadhorse</td>
<td>2500</td>
<td>36%</td>
<td>Daily max</td>
<td>Treatment -</td>
<td>Daily Max: ↑ 4°C</td>
</tr>
<tr>
<td>Montana (Hitt, 2003)</td>
<td>Creek</td>
<td>514</td>
<td>100%</td>
<td>Daily min</td>
<td>control</td>
<td>Daily Min: No change</td>
</tr>
<tr>
<td>Southern Oregon</td>
<td>Stream A</td>
<td>Total of 420 ha</td>
<td>High intensity burn (NA%)</td>
<td>Daily max</td>
<td>Within reach</td>
<td>Max obs: ↑ 10 °C</td>
</tr>
<tr>
<td>Oregon (Amaranthus et al., 1989)</td>
<td>Stream B</td>
<td>337</td>
<td>100%</td>
<td>Daily max</td>
<td>treatment -</td>
<td>Max obs: ↑ 6.2 °C</td>
</tr>
<tr>
<td>Central Idaho</td>
<td>Pidgeon Creek</td>
<td>440</td>
<td>55.7%</td>
<td>Daily max</td>
<td>control</td>
<td>Sept-May: No difference</td>
</tr>
<tr>
<td>(Royer and Minshall, 1997)</td>
<td>Grave Creek</td>
<td>337</td>
<td>100%</td>
<td>Daily max</td>
<td>control</td>
<td>Sept-May: No difference</td>
</tr>
<tr>
<td>Yellowstone National Park (Minshall et al., 1997)</td>
<td>Fritzer Creek</td>
<td>829</td>
<td>63.9%</td>
<td>Daily max</td>
<td>treatment -</td>
<td>Significant ↑ (p &lt; 0.01)</td>
</tr>
<tr>
<td>Boise River Basin, Idaho (Dunham et al., 2007)</td>
<td>Four streams</td>
<td>NA</td>
<td>High to low intensities (NA%)</td>
<td>Summer mean and maximum</td>
<td>Before-after, treatment-control</td>
<td>Stream pair 1: Significant ↑ for a decade post-fire Stream pair 2: No difference 1 yr post-fire</td>
</tr>
<tr>
<td>Southcentral B.C. (Leach and Moore, in press)</td>
<td>Fishtrap Creek</td>
<td>13500</td>
<td>75%</td>
<td>Spot measurements</td>
<td>Before - after</td>
<td>Significant ↑ (p &lt; 0.001) in summer only</td>
</tr>
</tbody>
</table>
1.3 Research questions and thesis structure

The review in Section 1.2 has identified a number of knowledge gaps in the understanding of stream energy exchange processes, and these form the context for the study presented here. The overall objective of this study was to contribute to our understanding of the physical controls on stream temperature at the reach scale, particularly in the context of a reach that had been influenced by a wildfire that killed most of the riparian vegetation. The specific research questions addressed by the thesis are:

1. What is the within-reach spatiotemporal variability in riparian microclimate? Do single measurements of riparian air temperature, humidity, wind speed and net radiation adequately represent reach-scale conditions? How sensitive are computed sensible and latent heat fluxes to the use of upland meteorological data?

2. What is the role of reach-scale surface-subsurface water interactions on the thermal regime of a stream? How do reach-scale temperature patterns depend on the spatial pattern of gaining and losing reaches?

3. What are the energy dynamics associated with standing dead riparian vegetation and its implication for stream temperature? How does the effect of the standing dead vegetation compare with pre-disturbance vegetation and a no-vegetation scenario representing the effects of salvage harvesting?

The remainder of the thesis is organized as follows. Chapter 2 describes the study site, field monitoring program and the methods of data analysis. Chapter 3 presents the results of the field monitoring program and data analysis. Chapter 4 discusses how the results address the primary research questions outlined above. Chapter 5 summarizes the main conclusions of the study and identifies topics for further research.
Chapter 2

Study site and methods

2.1 Study site - Fishtrap Creek

2.1.1 Location and general site description

The Fishtrap Creek catchment is located approximately 50 km north of Kamloops, British Columbia, in the Interior Plateau physiographic region of British Columbia (Figure 2.1). The catchment area is approximately 170 km$^2$ at the confluence with the North Thompson River and approximately 135 km$^2$ at a Water Survey of Canada (WSC) monitoring weir located 6 km upstream from the North Thompson River confluence. During the 2003 summer, a high intensity wildfire ignited and burned an estimated 75% of the Fishtrap Creek watershed, including significant portions of the riparian vegetation.

This study focused on a 1.5 km reach of Fishtrap Creek, extending upstream from the WSC weir to the Skull Creek and Fishtrap Creek confluence. At the midpoint of the study reach a spring emerges and flows for approximately 60 m before discharging into Fishtrap Creek. For this thesis the use of ‘Upper Subreach’ refers to Fishtrap Creek downstream of the Skull Creek confluence and upstream of the spring. The ‘Lower Subreach’ refers to Fishtrap Creek downstream of the spring and upstream of the WSC weir. The study began May 2007 and continued into the fall of that year. However, this thesis will focus primarily on data collected in July and August 2007.

2.1.2 Physiography, climate and hydrology

The elevation of the catchment ranges from 370 m at the North Thompson River confluence to 1600 m on the high plateau. The stream channel through
Chapter 2. Study site and methods

Figure 2.1: Map of the Fishtrap Creek catchment. The inset map locates Fishtrap Creek in relation to Kamloops and Vancouver, British Columbia.
the upper reaches (including the Upper Subreach) of the Fishtrap Creek catchment is incised into the plateau and is tightly coupled to the hillslopes. Near the Lower Subreach, the floodplain widens as the creek intersects a glacial meltwater channel that follows a major fault line (Phillips, 2007).

The study area has a semi-arid climate exhibiting hot and dry summers and short and mild winters. Data from the Mayson Lake snow research area, located approximately 15 km from the Fishtrap Creek catchment, indicate that the upper plateau areas receive about 700 mm of precipitation annually, 60% of which falls as snow (Winkler et al., 2005). Surficial geology of the study area is dominated by thick deposits of glacial drift except for bedrock outcrops on hillslopes. Soils are generally thin and poorly developed.

The riparian forest prior to the wildfire consisted of mature alders, cottonwoods and a variety of conifers. During the 2007 study period the riparian zone of the Fishtrap Creek study reach consisted of standing dead defoliated trees and forbaceous shrubs and fireweed. This understory plant regrowth reached a maximum growth height of 1 to 2 m during the study period.

Water Survey of Canada has monitored streamflow at the weir since the 1970s. Fishtrap Creek has a snowmelt dominated hydrological regime (Figure 3.2). Peak discharge occurs during the freshet period from March to June, where on average the discharge peaks at approximately 5 to 6 m$^3$s$^{-1}$. July and August, the period of focus of this study, are dominated by low flows typically less than 0.5 m$^3$s$^{-1}$.

### 2.2 Field measurements

#### 2.2.1 Reach-scale hydrology

Five distinct approaches were employed to characterize the hydrology of the study reach at Fishtrap Creek. Streamflow measurements at six locations throughout the study reach indicated net gains from or losses to the subsurface. Longitudinal electrical conductivity surveys and water chemistry samples provided further insight into the spatiotemporal stream-groundwater
interactions (Moore et al., 2008). Riparian zone monitoring wells were used to characterize hydraulic gradients between the stream and riparian subsurface water. Finally, stream bed temperatures also helped discern water flowpathways through the channel bed, as areas with downwelling typically have weak temperature gradients compared to areas with groundwater discharge (Silliman and Booth, 1993).

The spring was identified as a potential concentrated source of hyporheic discharge. However, local-scale hyporheic exchange was not characterized in this study primarily because sediment size and structure of the riparian zone and channel bed made installing wells and piezometers difficult.

**Stream gauging**

Streamflow was measured using the dry salt injection method (Hudson and Fraser, 2005) and the current meter method (Dingman, 2002). The dry salt injection method was used at streamflow measurement sites Q1, Q2, Q3, and Q4 while the current meter method was used at sites Q5 and Q6 (Figure 2.2). The method selected for each measurement site was determined by that site’s channel and flow characteristics. The dry salt injection method is better suited for a stream reach with highly turbulent flows to ensure complete mixing and a satisfactory mixing length with minimal pools and other backwater areas (Hudson and Fraser, 2005). Current metering is better suited for stream subreaches where flows are not highly turbulent, are sufficiently deep to use the current meter, and the channel cross-section has a relatively uniform geometry. Also, because current metering estimates discharge at one point along the subreach, the presence of pools and other backwater areas upstream do not influence the accuracy of the measurement. It would have been desirable to compare streamflow measurement methods by making measurements at the same site using both methods. However, this was not possible at Fishtrap Creek as none of the streamflow sites was favourable for accurately using both methods.

The dry salt injection method involved injecting a known mass of salt into the stream at the upstream end of the subreach and monitoring streamwa-
Chapter 2. Study site and methods

Figure 2.2: Map of the Fishtrap Creek study site indicating the locations of the continuous stream temperature measurements, stream discharge measurements, meteorological stations and the WSC weir.
ter electrical conductivity 75 to 150 m downstream, using a WTW™ handheld conductivity meter connected to a Campbell Scientific CR510 datalogger. The logger scanned at 1 second intervals and averaged and recorded every 5 seconds. To facilitate thorough mixing of the injected salt, stream subreaches were selected to have sufficiently turbulent flow, minimal pools and other backwater areas and no tributaries. Electrical conductivity was adjusted to a standard temperature of 25 °C using the nonlinear adjustment built into the WTW™ meter.

Prior to injecting the salt, the background streamwater electrical conductivity was noted. After injection of the salt the streamwater electrical conductivity was logged until the value returned to the background value. An on-site calibration was performed for each measurement to relate measured electrical conductivity to salt concentration. This calibration was done by first dissolving 1 g of salt into 1 L of stream water. Another 1 L of stream water was measured and its initial electrical conductivity was recorded. Five millilitre increments of salt solution were repeatedly mixed into the 1 L of stream water until the electrical conductivity exceeded the value recorded during the dry salt injection measurement.

Combining the measurement and calibration data, the stream discharge, \( Q \) (m\(^3\)s\(^{-1}\)), can be estimated by the dry salt injection method as:

\[
Q = \frac{M}{b \cdot I}
\]  

(2.1)

where \( M \) is the mass of salt (g) injected into the stream, \( b \) is the slope of the calibration (g cm/µSm\(^{-3}\)) and \( I \) is the area under the plot of electrical conductivity over time (µSm\(^{-1}\) s) measured downstream end of the subreach.

The current meter method used in this study was adapted from Dingman (2002). A Marsh-McBirney Model 2000 Flo-Mate current meter, with electromagnetic sensor and top-setting wading rod, was used. The 60 second average velocity at 60% of the water depth was measured at 10-20 cm increments across the channel width. The partial discharge \( q_i \) for section
Chapter 2. Study site and methods

\[ q_i = v_i d_i w_i \]  \hspace{1cm} (2.2)

where \( v_i \) is the mean velocity (ms\(^{-1}\)) of section \( i \), \( d_i \) is the depth of water (m) of section \( i \), and \( w_i \) is the width (m) of section \( i \). The partial discharges were summed to determine the total discharge, \( Q \) (m\(^3\)s\(^{-1}\)).

**Electrical conductivity surveys**

The identified water sources of the Fishtrap Creek study reach (Skull Creek, Fishtrap Creek above the Skull Creek confluence and the spring) were manually monitored for electrical conductivity whenever each of these locations was visited. Electrical conductivity was also measured every 25-40 m along the study reach. A spring located outside of the study reach was also monitored because its high conductivity suggested it was dominantly groundwater.

**Water chemistry**

Manual water chemistry samples were taken monthly from Fishtrap Creek and the identified Fishtrap Creek water sources (Skull Creek, Fishtrap Creek above Skull Creek and the spring). The spring located outside the study reach which was monitored for electrical conductivity, was also sampled for chemistry and used as a surrogate for regional groundwater. The samples were analyzed for nitrate, chloride, silica and various additional cations (Al\(^{3+}\), Ba\(^{2+}\), Ca\(^{2+}\), Co\(^{2+}\), Cr\(^{6+}\), Cu\(^{2+}\), Fe\(^{2+}\), K\(^+\), Mg\(^{2+}\), Mn\(^{2+}\), Na\(^+\), Ni\(^{2+}\), Pb\(^{2+}\), Sr\(^{2+}\) and Zn\(^{2+}\)). Nitrate and chloride were analyzed by the Lachat QuickChem autoanalyzer (Lachat Instruments, Milwaukee, WI). The metal cations were analyzed using inductively coupled plasma atomic emission spectroscopy (ICP-AES).

**Riparian zone monitoring wells**

Wells were constructed from PVC pipe and had a length of 1.5 m and a diameter of 19 mm. Slots were cut into the bottom 40-60 cm of the pipe to
facilitate water exchange between the surrounding substrate and the well. Wells were installed by inserting a capped piece of rebar into the pipe and hammering the rebar and well into the ground. Wells were typically installed to a depth of 1.1 to 1.3 m below the ground surface. At most sites, depth of installation was limited by the difficulty of driving the wells into the coarse substrate.

Thirty-three wells were installed at the study site. Nearly all the wells were installed in the riparian zone of the lower subreach. Few were installed in the riparian zone of the upper subreach due to coarse substrate making well installation difficult. Wells were installed in transects from 1 to 30 m distances from the stream edge.

Well water levels were measured over the course of the study period. Prior to measurement, wells were purged using tygon tubing attached to a large syringe. Wells were purged and then left to recharge for approximately an hour before a water level was measured. The water level was determined by inserting two wires connected to a battery (creating an open electrical circuit) fastened to the end of a ruler into the well until the wires contacted the water and closed the circuit. Closing the circuit was signalled by a small buzzer connected in series with the wires. Measurements were reproducible to ±0.5 cm.

Stream bed temperature profiles

Stream bed temperature profiles were primarily installed to estimate bed heat conduction rates (see Section 2.2.5 for details). Stream bed temperature profiles can also be used to determine flow pathways through the stream bed (Silliman and Booth, 1993). If stream water is being lost to the subsurface, bed temperatures will be similar to the stream temperature. If subsurface water is discharging into the stream through the bed, a pronounced temperature gradient into the stream bed may be present (e.g. Story et al. 2003).
2.2.2 Stream temperature monitoring

Continuous stream temperature measurements were made using submersible Onset Tidbit V2 temperature data loggers (accurate to ±0.2 °C). The loggers were programmed to record and store stream temperature readings every 10 or 20 minutes. Loggers were fitted with radiation shields made from white PVC pipe, with holes drilled through the pipe to ensure water exchange. Loggers were deployed at ten locations throughout the study reach (Figure 2.2). Measurement sites T(a, b, c, d, h, i, j, k) were distributed throughout the study reach and were located at sites that were laterally well mixed. The lateral mixing and subsequent uniformity in stream temperature was confirmed with manual lateral stream temperature surveys prior to logger installation. Measurement sites T(e, f) measured the spring water temperature at two locations where water emerged from the subsurface. Measurement site T(g) measured the spring water temperature just prior to where the spring discharged into the study reach.

2.2.3 Meteorological measurements

Three automated meteorological stations were installed to characterize spatiotemporal variability in riparian microclimate conditions and as input data for the energy budget models. Two meteorological stations were installed within the study reach, one at 440 m and one at 1342 m downstream of the Skull Creek confluence (Figure 2.2). The instruments were located approximately 1 m above the stream surface (Figure 2.3). The third meteorological station was installed approximately 200 m from the WSC monitoring weir on a deforested local topographic high. The instruments at this site were unobstructed by vegetation or topography and were therefore used as a surrogate for above canopy conditions.

The meteorological variables measured at the stations were air temperature, relative humidity, shortwave radiation, wind speed and precipitation (at the open site only). Stream temperature was also measured at the stream sites. Air temperature and relative humidity were measured with a HMP45C-L probe fitted with a radiation shield. The air temperature sen-
Chapter 2. Study site and methods

The sor was accurate to $\pm 0.3$ °C over the range observed at the study site. The relative humidity probe was accurate to $\pm 3\%$ RH for the 0 to 90% RH range and $\pm 5\%$ for the 90 to 100% RH range. Shortwave radiation was measured with a CMP3 Kipp and Zonen pyranometer. Wind speed was measured with a Met One 3-cup anemometer which had a starting threshold of 0.447 $\text{ms}^{-1}$. Precipitation at the open site was measured with a tipping bucket rain gauge (0.2 mm per tip). Stream temperature at the two stream stations was measured with 107-L temperature thermistors. All instruments were scanned every 10 s and averaged every 10 min (or summed in the case of the precipitation gauge) by Campbell Scientific CR10x data loggers.

Due to instrument failure, incoming shortwave radiation was not measured during a two week period at the open site. Therefore, incoming shortwave radiation measured at the Mayson Lake study site (Winkler et al., 2005) was used in a statistical model to estimate the missing data. The Mayson Lake study site is located approximately 15 km northwest of Fishtrap Creek. A Licor pyranometer was scanned every 60 s and averaged every 60 min by a Campbell Scientific CR10x data logger.

Net radiation was also measured above the stream surface using a Kipp and Zonen net radiometer. Five locations along the study reach where monitored at different times during the study period. The length of time the net radiometer was installed at each site ranged from one to twelve days. The net radiometer was positioned approximately 30-40 cm above the stream surface. The net radiometer was scanned every second and averaged every 10 min using a Campbell Scientific CR10 logger.

2.2.4 Hemispherical canopy photographs

Hemispherical canopy images were used, in conjunction with meteorological data, to model radiative exchanges. A Nikon fisheye converted FC-E8 lens and a Nikon Coolpix 4500 4.0 mega pixel digital camera, set on Fisheye mode and highest image quality, were used to capture the images. Two or three images were taken across the stream width at 30 to 40 m intervals along the study reach. Images were oriented to north using a compass and
Figure 2.3: Upper Site meteorological station.
the camera was levelled prior to the capturing of each image. Images were taken approximately 10-20 cm above the stream surface. Hemispherical images were also taken at the locations where net radiation was measured (Section 2.2.3) and at the two stream meteorological station pyranometers. Images were taken on clear sky days, prior to sunrise or after sunset, or on overcast days to ensure uniform sky conditions to facilitate image processing.

2.2.5 Stream bed temperatures

Four locations were monitored for bed temperature profiles. All four sites were located near the lower subreach meteorological station. It was intended to install bed temperature profiles at more sites, including the upper subreach; however, the coarse bed material made installation difficult. At each profile location, bed temperatures were measured at 1, 5, 10 and 30 cm depths using copper-constantan thermocouple wire. The thermocouple wires were connected to a multiplexer and CR21x logger. However, due to logger failure, only manual measurements of bed temperatures were obtained. An OMEGA handheld thermocouple reader was used for manual measurements and reported temperature to the nearest 0.1 °C.

2.3 Analysis and modelling

2.3.1 Principal components analysis of streamwater chemistry

Principal components analysis (PCA) was performed on streamwater chemistry data. PCA was used as an exploratory tool to estimate the number and composition of source water components contributing to the streamwater chemistry mixture (Christophersen and Hooper, 1992). The variables were scaled prior to analysis and eigenvalues of near or greater than one were considered significant. PCA’s were performed separately on the full, upper and lower reaches using the following variables: Si, Ca, K, Mg and Na. Silica has been employed as an indicator of runoff contributions from deep subsurface waters characterized by a relatively long contact time (Ladouche
et al., 2001). Other researchers in the Pacific Northwest have found that certain cations, specifically K, may be used as an indicator of surface/shallow subsurface flow (Whyte, 2004). The other streamwater chemistry variables analyzed in the lab were not included in the PCA because either their concentrations did not exceed detection limits or a complete dataset did not exist.

2.3.2 Net radiation model

A model for net radiation was used to account for spatial heterogeneity in riparian vegetation structure and topography along the study reach. The model and procedure were adapted from Moore et al. (2005b), which used hemispherical photos to quantify vegetation and shading effects along the study reach. The net radiation, \( Q^* \) (Wm\(^{-2}\)), occurring at the stream surface can be expressed as the sum of its short and long wave components:

\[
Q^* = K^* + L^*
\]

where \( K^* \) is the net short wave radiation flux density at the stream surface (Wm\(^{-2}\)) and \( L^* \) is the net long wave radiation flux density at the stream surface. The following sections will outline how each of the components on the right hand side of Equation 2.3 were calculated.

**Net short wave radiation**

The net short wave radiation component of the model, \( K^* \), can be expressed as

\[
K^* = (1 - \alpha) \left[ D(t)g(t) + S(t)f_v \right]
\]

where \( \alpha \) is the albedo of the stream, \( D(t) \) is the direct component of incident solar radiation at time \( t \) (Wm\(^{-2}\)), \( S(t) \) is the diffuse component of incident solar radiation at time \( t \) (Wm\(^{-2}\)) and \( f_v \) is the sky view factor.

Albedo measurements were made at the study site using a hand held pyranometer connected to a voltmeter. The pyranometer was first held face up and level at 5-10 cm above the stream surface until a stable reading was
achieved. The pyranometer was then held face down and level at 30-50 cm above the stream surface (in order to reduce any instrument shading effect) until a stable reading was achieved. The ratio of the two values provided an estimate of stream albedo. Measurements were retaken or aborted if sky conditions were changing rapidly. Nine sample sites were monitored, comprised of three sets of three water classification types: pools, glides and riffles. The nine sites were sampled four times during the study period.

A surrogate for incident solar radiation above the forest canopy was measured using a pyranometer at the open site meteorological station (Section 2.2.3) and was used as input to Equation 2.4. The diffuse component of incident solar radiation was not measured at the study site. Therefore, the measured above-canopy incident solar radiation was partitioned into the diffuse and direct components by calculating the diffuse fraction $k_d$ (ratio of the diffuse-to-global solar radiation) using the procedure presented by Erbs et al. (1982):

$$
k_d = \begin{cases} 
1.0 - 0.09k_t & \text{for } k_t \leq 0.22 \\
0.951 - 0.1604k_t + 4.388k_t^2 - 16.638k_t^3 + 12.336k_t^4 & \text{for } 0.22 < k_t \leq 0.80 \\
0.165 & \text{for } k_t > 0.80 
\end{cases} \quad (2.5)
$$

where $k_t$ is the clearness index (ratio of the global-to-extraterrestrial solar radiation).

Gap fractions as a function of zenith angle ($\theta$) and azimuth ($\psi$), $g_* (\theta, \psi)$, were derived by analysing the hemispherical images with the Gap Light Analyser software (Frazer et al., 1999), using $5^\circ$ increments for both zenith and azimuth angles. The canopy gap function, $g(t)$, was derived from $g_* (\theta, \psi)$ by computing the solar zenith and azimuth angles as a function of time, $t$, using equations in Iqbal (1983). The view factor was computed as

$$
f_v = \frac{1}{\pi} \int_0^{2\pi} \int_0^{\pi/2} g_* (\theta, \psi) \cos \theta \sin \theta \cdot \, d\theta \cdot \, d\psi \quad (2.6)
$$

where $\theta$ is the solar zenith angle (vertical = 0), $\psi$ is the azimuth angle, and $g_* (\theta, \psi)$ is the gap fraction at sky position $\theta$, $\psi$. The double integral was
approximated by summations using an interval of 5° for both zenith and azimuth angles.

**Optimum threshold for analysing canopy photographs**

An optimum threshold value was needed for processing the hemispherical images. The optimization was done by applying threshold values of 120 to 190, at 10 unit increments, to the hemispherical images associated with the two pyranometers at the upper and lower subreach meteorological station sites. For each threshold value the incoming solar radiation was modelled using Equation 2.4 without the albedo component. The model was run separately for clear sky days and non-clear-sky days to examine any confounding error associated with the estimated direct and diffuse incident solar radiation components. For each site and sky condition the root mean square error (RMSE) and mean bias error (MBE) were calculated to determine the optimum threshold value.

**Net long wave radiation**

The long wave radiation emitted from the atmosphere, topography and vegetation and reaching the stream surface can be expressed as

\[ L \downarrow = [f_v \varepsilon_a + (1 - f_v)\varepsilon_{vt}] \sigma (T_a + 273.2)^4 \]  

(2.7)

where \( f_v \) is the sky view factor, \( \varepsilon_a \) is the emissivity of the atmosphere, \( \varepsilon_{vt} \) is the emissivity of the vegetation and terrain, \( \sigma \) is the Stefan-Boltzmann constant, and \( T_a \) is the air temperature 1 m above the stream surface measured at the nearest climate station (°C). The longwave radiation emitted by the water surface is

\[ L \uparrow = \varepsilon_w \sigma (T_w + 273.2)^4 \]  

(2.8)

where \( \varepsilon_w \) is the emissivity of the stream, \( \sigma \) is the Stefan-Boltzmann constant, and \( T_w \) is the stream temperature measured at the nearest Tidbit logger (°C).
Figure 2.4: An example of a hemispherical image taken above the stream surface and processed by Gap Light Analyzer (Frazer et al., 1999). a) a hemispherical image with a 5° azimuth and zenith grid overlay. b) a Gap Light Analyzer processed hemispherical image using an optimized threshold value of 160.
Chapter 2. Study site and methods

The net longwave radiation exchange is then

\[ L^* = \varepsilon_w L \downarrow - L \uparrow \]  \hspace{1cm} (2.9)

Day time atmospheric emissivity was calculated by first using the Prata (1996) equation for clear sky conditions

\[ \varepsilon_0 = 1 - (1 + w)\exp\left[-(1.2 + 3.0w)^{0.5}\right] \]  \hspace{1cm} (2.10)

where \( \varepsilon_0 \) is the clear sky atmospheric emissivity and \( w \) is the precipitable water content of the atmosphere (cm), expressed as

\[ w = 465\left[e_a/(T_a + 273.2)\right] \]  \hspace{1cm} (2.11)

where \( e_a \) is the atmospheric vapour pressure (kPa), and \( T_a \) is the air temperature (°C), both measured at the nearest stream climate station to the sample site.

Because the sky conditions during the study period were dominantly a mix of clear and cloudy periods, it was necessary to account for the presence of clouds when calculating the atmospheric emissivity. The procedure used in this study to account for cloudy sky conditions, in the absence of direct observations, was adapted from Arnold et al. (1996) and Brock and Arnold (2000). An approximation of cloudiness, \( n \), can be gained by comparing measured \( K \downarrow \) with the theoretical maximum incoming short wave radiation under a cloud free sky, \( K \downarrow_{max} \). \( K \downarrow_{max} \) can be expressed as

\[ K \downarrow_{max} = I_0\Psi(P/P_0)\cos\theta \]  \hspace{1cm} (2.12)

where \( I_0 \) is the solar constant (1367 Wm\(^{-2}\)), \( \Psi \) is the clear sky transmissivity (0.75), \( P \) is atmospheric pressure (calculated as 94.2 kPa for Fishtrap Creek, following Stull (2000) using a site elevation of 620 m), \( P_0 \) is mean atmospheric pressure at sea level (101.3 kPa) and \( \theta \) is the solar zenith angle. The approximation of cloudiness, \( n \), can then be calculated linearly from the ratio of \( K \downarrow : K \downarrow_{max} \), when their ratio is 1, \( n = 0.0 \) and \( n \) increases as
Chapter 2. Study site and methods

the ratio decreases. It is assumed that \( n = 1.0 \) for \( K ↓: K ↓_{max} \) ratios of \( \leq 0.2 \). The non-clear-sky atmospheric emissivity, \( \varepsilon_a \), can then be calculated as

\[
\varepsilon_a = (1 + \kappa n) \varepsilon_0 \tag{2.13}
\]

where \( \varepsilon_0 \) is the clear sky emissivity, calculated in Equation 2.10, \( n \) is the cloudiness, and \( \kappa \) is a constant depending on cloud type. Following Braithwaite and Olesen (1990), a value of 0.26 is used for \( \kappa \), the mean value for altostratus, altocumulus, stratocumulus, stratus and cumulus cloud types.

Equation 2.13 can only be calculated for daytime periods. Night time values of atmospheric emissivity were calculated as the mean of the daytime values before and after the night of interest.

Emissivities for water and vegetation/terrain were estimated by optimizing these values within the net radiation model (Equations 2.4, 2.7 and 2.8) for night-time conditions (when \( L^* = Q^* \)). Net Radiation Evaluation Site 2 was chosen for the optimization because it contained a large number of days (11) with both clear and non-clear periods. The BFGS optimization method with upper and lower bounds (Byrd et al., 1995) was used.

2.3.3 Energy budget model

A deterministic reach-scale energy budget model was developed to explore the physical controls responsible for the observed stream temperature patterns at Fishtrap Creek. A Lagrangian modelling approach was used to predict downstream temperatures. This modelling approach divides the stream into a series of segments bounded by nodes (indexed by \( i \)). For every time step, \( \Delta t \) (s), a water parcel (indexed by \( j \)) is released from the upstream boundary at an initial stream temperature based on measurements. As the water parcel flows downstream from node \( i \) to \( i + 1 \) the model computes the heat inputs (Equation 2.14), the change in stream discharge (Equation 2.15) and the consequent change in stream temperature over the stream segment (Equation 2.16):

\[
\frac{dT}{dx} = \frac{W [Q^*(i, t) + Q_h(i, t) + Q_e(i, t)] + q_{in}[T_{in}(t) - T_w(i)]}{C \cdot F(i)} \tag{2.14}
\]
Chapter 2. Study site and methods

\[ \frac{dF}{dx} = q_{in} \]  \hspace{1cm} (2.15)

\[ T_w(i + 1, t + 1) = T_w(i, t) + \Delta x \cdot \frac{dT}{dx} \]  \hspace{1cm} (2.16)

where \( W \) is the mean stream width (m), \( Q^*(t) \), \( Q_h(t) \) and \( Q_e(t) \) are the net radiation, sensible and latent heat fluxes (W m\(^{-2}\)) at time \( t \) and node \( i \), respectively, \( C \) is the heat capacity of water (4.18 \times 10^6 J m\(^{-3}\) C\(^{-1}\)), \( F(i) \) is the stream discharge (m\(^3\) s\(^{-1}\)) at stream node \( i \), \( q_{in} \) is the rate of groundwater inflow per unit length of stream (m\(^3\) s\(^{-1}\) m\(^{-1}\)), \( T_{in} \) is the groundwater temperature and \( T_w(i) \) is the stream temperature at stream node \( i \). The stream segment length (\( \Delta x \)) is calculated as the product of the mean stream velocity (m s\(^{-1}\)) and the time step (s). The model was evaluated by comparing the predicted downstream temperatures to the observed downstream temperatures for the reach of interest.

The energy budget model was applied to three reaches at Fishtrap Creek: the upper subreach, the lower subreach and the full reach. The upper subreach was bounded by sites T(a) and T(d), the lower subreach by sites T(h) and T(j), and the full reach by sites T(a) and T(j). Determination of the input variables to the model is outlined in the following sections. A bed heat conduction term was not included in the model due to an incomplete data set of stream bed temperatures.

Net radiation

Incident solar and longwave radiation were estimated at the reach scale by averaging the gap fractions at each sky position for all hemispherical images that were taken at the stream reach. These values were then used in the net radiation model (Section 2.3.2).

Convective heat fluxes

The latent heat flux \( (Q_e) \) was estimated using a Penman-type equation presented by Webb and Zhang (1997): \( Q_e = 285.9(0.132 + 0.143 \cdot U)(e_a - e_w) \)  \hspace{1cm} (2.17)
where $U$ is the wind speed (ms$^{-1}$) and $e_a$ and $e_w$ are the vapour pressures (kPa) of the air and water, respectively. Saturation vapour pressure ($e_{sat}$) was calculated as a function of air or water temperature, $T$ (K), following Stull (2000):

$$e_{sat} = e_o \cdot \exp \left[ \frac{L_v}{R_v} \left( \frac{1}{T_o} - \frac{1}{T_w} \right) \right] \quad (2.18)$$

where $e_o = 0.611$ kPa and $T_o = 273$ K are constants, $L_v = 2.5 \cdot 10^6$ Jkg$^{-1}$ is the latent heat of vaporization and $R_v = 461$ JK$^{-1}$kg$^{-1}$ is the gas constant for water vapour. The vapour pressure at the water surface was assumed to equal $e_{sat}$, while the actual vapour pressure of the air ($e_a$) was calculated as:

$$e_a = \left( \frac{RH}{100} \right) e_{sat} \quad (2.19)$$

where $RH$ is the relative humidity measured at the nearest stream meteorological station.

The sensible heat flux ($Q_h$) was estimated as:

$$Q_h = \beta \cdot Q_e \quad (2.20)$$

where $\beta$ is the Bowen Ratio, calculated as:

$$\beta = 0.66 \cdot (P/1000) \cdot [(T_w - T_a)/(e_w - e_a)] \quad (2.21)$$

where $P$ is air pressure, which was assumed constant at 94.2 kPa for Fishtrap Creek, following Stull (2000) using a Fishtrap Creek site elevation of 620 m and given that monthly average air pressure at the Kamloops airport is 97 kPa.

**Stream-subsurface exchanges**

The advective components of the energy budget model ($F$ and $q_{in}$) were determined from field measurements of stream-subsurface interactions (Section 2.2.1). For the upper subreach, which was losing during the study period, the stream discharge ($F$) was assumed to decrease linearly over the reach length and the rate of groundwater inflow ($q_{in}$) was assumed to equal zero.
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The lower subreach was also observed to be dominantly losing during the study period; however, there were some suggestion that the lower subreach did have localized subsurface inflow occurring despite the net discharge loss (see Section 3.2.7). Therefore, the rate of groundwater inflow was optimized in the stream energy budget model for stream discharge measurements from 29 July, and this optimized inflow rate was used for all other dates. Stream discharge for the lower subreach was assumed to decrease linearly over the reach length while the rate of groundwater inflow was assumed to be constant.

When applying the energy budget model to the full reach, the stream discharge patterns for the upper subreach and lower subreach were determined as outlined above. The spring discharge contribution was treated as a discrete input at 751 m downstream of the Fishtrap Creek and Skull Creek confluence. Stream temperature at the node below the spring \([T_w(i + 1)]\) was calculated using a simple mixing equation:

\[
T_w(i + 1) = \frac{T_w(i)F(i) + T_{sp}F_{sp}}{F(i) + F_{sp}}
\]  

(2.22)

where \(T_w(i)\) is the upstream node temperature, \(F(i)\) is the upstream node discharge, \(T_{sp}\) is the temperature of the spring water and \(F_{sp}\) is the spring discharge.

**Bed heat conduction**

Bed heat conduction, \(Q_c\), was calculated as:

\[
Q_c = K_c \cdot (T_{0.05} - T_{0.01})/0.04m
\]  

(2.23)

where \(K_c\) is the thermal conductivity of the streambed material (Wm\(^{-1}\)K\(^{-1}\)), \(T_{0.05}\) and \(T_{0.01}\) are bed temperatures at depths of 0.05 m and 0.01 m, respectively. The thermal conductivity was assumed to equal 2.6 Wm\(^{-1}\)K\(^{-1}\) based on estimates by Lapham (1989) using a porosity value of 0.30, which is typical for gravels (Freeze and Cherry, 1979).
2.4 Virtual experiments

In order to explore the physical controls responsible for the stream thermal regime at Fishtrap Creek, virtual experiments were conducted using the developed energy budget model (Section 2.3.3). The virtual experiments focused on the roles of stream-subsurface interactions and standing dead riparian vegetation.

2.4.1 Stream-subsurface interactions

A virtual experiment was conducted for Fishtrap Creek by exploring the role of stream-subsurface interactions on the Fishtrap Creek thermal regime. The measured hydrological conditions at Fishtrap Creek were used to simulate downstream temperatures, which were then compared to simulated stream temperature values under the conditions of no stream-subsurface interactions ($q_{in} = 0; \frac{dF}{dx} = 0$).

2.4.2 Canopy cover

A virtual experiment was conducted to investigate the processes controlling the observed stream temperature increase following wildfire at Fishtrap Creek (Leach and Moore, in press). Modelled net radiation and stream temperature changes along the reach for the current condition (standing dead trees) were compared to simulations for two scenarios, representing (a) removal of the standing dead trees (e.g., via post-fire salvage harvesting) and (b) pre-fire vegetation.

Scenario (a) was simulated by clipping the standing dead trees from the hemispherical canopy images, leaving only terrain as a source of shading and incoming longwave radiation. Scenario (b) was simulated by taking hemispherical canopy photographs along Jamieson Creek, which is located approximately 30 km south of Fishtrap Creek and has similar channel width and riparian vegetation to pre-fire conditions at Fishtrap Creek. The Jamieson Creek images were adjusted to have the same aspect and terrain shading as Fishtrap Creek within GLA.
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Figure 2.5: Processed hemispherical images using Gap Light Analyzer. a) a processed hemispherical image at Fishtrap Creek for the 2007 post-wildfire disturbance canopy cover conditions. b) the same hemispherical image, with the riparian vegetation removed leaving only the terrain.

Figure 2.6: Hemispherical images taken from the stream surface at a) Fishtrap Creek and b) Jamieson Creek. Jamieson Creek was used to simulate riparian vegetation structure conditions at Fishtrap Creek prior to the wildfire disturbance.
Chapter 3

Results

The chapter begins with an overview of the study period (Section 3.1), which is followed by the field measurement results used to characterize the reach-scale hydrology (Section 3.2), temperature patterns (Section 3.3) and the riparian microclimate (Section 3.4). Model development, evaluation and results for the net radiation model are presented in Section 3.6 and stream temperature model evaluation and results are presented in Section 3.7. Results from the virtual experiments are presented in Section 3.8.

3.1 Overview of the study period

The 2007 study period was characterized by a relatively warm and dry July to mid-August period followed by a wetter and cooler late-August to September period. For the study period, July, August and September mean air temperatures were 2.4 °C greater, no different and 0.6 °C lower, respectively, than the long term averages recorded at the Kamloops Airport (Table 3.1). The July and August total accumulated precipitation for 2007 was close to the long term average recorded at the Kamloops Airport.

Figure 3.1 presents continuous air temperature, relative humidity and accumulated precipitation recorded at the Open Site meteorological station from mid-July to September 2007. The highest air temperatures were experienced mid-July and were followed by a general cooling trend to the end of the study period. Four days (July 29 and August 9, 16 and 21) of intense field measurements (consisting of longitudinal stream discharge, electrical conductivity survey and wetted width measurements) for energy budget analyses were conducted during the study period. The antecedent conditions for these four days were as follows: July 29 was preceded by a
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<table>
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<th></th>
</tr>
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<td>23.4</td>
<td>21.2</td>
<td>23.7</td>
<td>23.3</td>
</tr>
<tr>
<td>August Air $T_{\text{mean}}$ ($^\circ$C)</td>
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<td>22.2</td>
<td>21.7</td>
<td>21.4</td>
<td>20.2</td>
</tr>
<tr>
<td>September Air $T_{\text{mean}}$ ($^\circ$C)</td>
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<td>14.4</td>
<td>14.8</td>
<td>16.4</td>
<td>14.6</td>
</tr>
<tr>
<td>Jul-Aug Total Precip (mm)</td>
<td>79.1</td>
<td>134.0</td>
<td>50.0</td>
<td>72.4</td>
<td>71.6</td>
</tr>
</tbody>
</table>

Table 3.1: Mean monthly air temperatures for July, August and September and total accumulated summer (July and August) precipitation recorded at the Kamloops Airport from 1951 to 2007.

week of dry, warm and clear sky conditions; August 9 was preceded by a rain event (3.2 mm) on August 8 and cool conditions; August 16 was preceded by dry and partly cloudy conditions; and August 21 was preceded by a rain event (9 mm), which occurred over August 19-21, and cool and overcast conditions.

Figure 3.2 places the mean daily stream discharge measurements made at the Water Survey of Canada weir during 2007 in the context of the maximum, mean and minimum mean daily discharges recorded at the weir between 1977 and 2007. The 2007 freshet period was earlier and had a slightly greater peak than the mean freshet values. The summer flows of July to September of 2007 were slightly lower than average and close to the minimum values recorded over the past 30 years.
Figure 3.1: Air temperature, vapour pressure (VP) and rainfall measured at the Open Site meteorological station from mid-July to September 2007.
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Figure 3.2: Plot of maximum, mean, and minimum mean daily discharges from 1977 to 2007 with 2007 highlighted in red.
3.2 Reach-scale hydrology

3.2.1 Streamflow variations

Manual streamflow measurements were made on five days during the study period. On four of the five days, streamflow measurements were made at multiple sites along the study reach, while on September 17 streamflow was only measured at the spring. The streamflow measurements suggest that the upper subreach was a net losing reach, while the lower subreach was also predominantly a net losing reach (Figure 3.3). On August 21, however, the lower subreach was net gaining, which was likely caused by riparian groundwater response to the precipitation event on August 20. Throughout the study period the measured discharge at the spring was constant at approximately 0.08 m$^3$s$^{-1}$ ($n = 5$) as were the stage measurements measured at a staff gauge associated with the spring ($n = 13$).

Water Survey of Canada mean daily discharge recorded at the weir were compared to corresponding instantaneous manual discharge measurements made approximately 10 m upstream of the weir (Figure 3.3). The weir and manual measurements closely agreed for August 9 and 16, partly due to minimal diurnal variations in discharge on those days. The weir and manual discharge measurements on August 21 did not agree (0.17 m$^3$s$^{-1}$ and 0.18 m$^3$s$^{-1}$, respectively). This disagreement was likely due to inaccuracies of the measurement methods or due to the temporal discharge response to the precipitation event on August 20 and the fact that the weir recorded hourly mean discharge values while the manual measurement represents an instantaneous discharge.

3.2.2 Electrical conductivity surveys

Longitudinal electrical conductivity surveys presented in Figure 3.4 help illustrate four points regarding the reach scale hydrology of Fishtrap Creek. (1) The overall EC of the reach increased over the study period, suggesting a shift from a snowmelt (low EC) dominated water source to a groundwater (high EC) source. (2) The influence of the spring located at 750 m increased
Figure 3.3: Longitudinal variations in stream flow measured downstream of the Skull Creek and Fishtrap Creek confluence. The corresponding WSC weir discharge measurements are indicated in grey. The location of the spring is shown.
over the study period because the flow above the spring decreased after the
freshet while the spring discharge remained constant. (3) There was little
change in longitudinal EC profiles for the upper subreach, suggesting no
inputs of chemically dissimilar water. This EC pattern was consistent with
the streamflow measurements, suggesting the upper subreach was losing.
(4) There were slight variations in the longitudinal EC profiles for the lower
subreach, particularly between 1000 and 1150 m downstream of Skull Creek.
This downstream EC variability was most obvious on July 14 and August
21, when EC decreased with downstream distance, suggesting an input of
chemically dissimilar (lower EC) water within this location. This EC pattern
was not consistent with the majority of the streamflow measurements, which
suggest the lower subreach was losing. However, the change in EC on August
21 is consistent with the observed change in streamflow on that date.

The electrical conductivity of Fishtrap Creek and its identified water
sources exhibited a similar temporal pattern (Figure 3.5). All sample sites
had a reduced EC during the freshet period and an increased EC through
the summer. The spring had the highest EC during the freshet period
and the second highest, behind Fishtrap Creek above Skull Creek, from
July onwards. These results suggest that the spring water was either from
a shallow groundwater source and thus influenced by the current year’s
snowmelt, or was hyporheic water originating from Skull and/or Fishtrap
Creek and possibly mixing with groundwater.

3.2.3 Water chemistry

Table 3.2 shows the PCA results of streamwater chemistry for the full, upper
and lower reaches. The full reach results indicate two significant principal
components, which implies three end-members contributing to the Fishtrap
Creek streamwater. PC1 is positively loaded on all variables, suggesting it
is associated with higher concentrations of these solutes. PC1 is positively
loaded on Si, which suggests it is associated with groundwater contributions.
PC2 is negatively loaded on Ca, Na and Si, suggesting it is associated with
more dilute concentrations of these solutes and less associated with ground-
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Figure 3.4: Longitudinal variations in stream electrical conductivity measured downstream of the Skull Creek and Fishtrap Creek confluence.
Figure 3.5: Electrical conductivity measurements from Fishtrap Creek and potential water sources.
water contributions. Potassium was positively loaded with PC2 and the presence of K has been suggested to be positively correlated with shallow subsurface/surface flow (Whyte, 2004).

Figure 3.6 shows a plot of the first and second principal components for the full-reach analysis. There is a clear shift between the July 14 samples and those for the other three dates. The July 14 samples were taken on the falling limb of the snowmelt freshet, and thus should be more dilute and influenced by water following shallow subsurface and possibly overland flow pathways during snowmelt than the other three samples, which were taken during late summer and autumn baseflow. Consistent with this hypothesis, the July 14 samples load negatively onto PC1, indicating overall lower concentrations, and positively onto PC2, indicating lower Si and higher K.

For the samples taken on Aug. 21, Sept. 6 and Oct. 13, the points for each date lie roughly along a line, with the points for Skull Creek and Fishtrap above Skull lying at the extremes. This pattern is consistent with the hypothesis that there is no influence of groundwater discharge originating outside the riparian zone, and that subsurface water discharging into the reach (including the spring) is hyporheic water originating from the two tributaries. For the samples taken on Jul. 14, the points suggest that the chemistry is defined by mixing of three end-members: Skull Creek, Fishtrap above Skull and the spring. The spring sample is more strongly correlated with PC2 than the other two putative end-members. If the spring is actually hyporheic water originating from Skull Creek and Fishtrap above Skull, as suggested by the baseflow samples, then one possible explanation is that the spring’s water chemistry on Jul. 14 was influenced by hyporheic recharge that occurred earlier in the freshet, which could have had a stronger PC2-type signature (i.e., lower Si and higher K). This behaviour of the spring, shifting from being chemically unique during the freshet to being a simple mixture of water from the two tributaries, is loosely consistent with the EC patterns (Figure 3.5).

The upper reach PCA results indicate one significant principal component, which implies two end-members contributing to the upper subreach streamwater. The two end-members for the upper subreach are likely Skull
Table 3.2: PCA results of streamwater chemistry for the full, upper and lower reaches. Only the first two components are shown, because the third components had eigenvalues substantially lower than unity.

Creek and Fishtrap Creek above Skull Creek. The lower reach PCA results indicate two significant principal components, which implies three end-members contributing to the lower subreach streamwater. The three end-members for the lower subreach are likely Fishtrap Creek above the spring and the spring, with the spring being accounted for twice, due to a distinct shift in its chemical signature between July 14 and the three later sample dates.

### 3.2.4 Riparian zone monitoring wells

Nearly all wells held some water when installed during May and June. However, from July to the end of the study period all the riparian zone monitoring wells were dry, indicating that for the lower subreach, where nearly all the wells were located, the groundwater table was at least 1.1 to 1.3 m below the ground surface.

### 3.2.5 Stream bed temperature profiles

Stream bed temperature profiles for the lower subreach presented in Section 3.3.2 show only small bed temperature gradients, which suggests rapid infiltration of stream water, consistent with the observed streamflow losses.
Figure 3.6: Bivariate plot of the first and second principal components for the PCA on the streamwater chemistry of the full reach. Samples are identified by location (symbols) and date (colours).
3.2.6 Spring contribution

The contribution of the spring to downstream discharge over the study period was estimated by solving mixing equations using measured EC and mean daily temperature values for Fishtrap Creek above the spring, the spring and Fishtrap Creek below the spring. The results presented in Figure 3.7 illustrate the growing contribution of the spring to downstream discharge through the study period. During the freshet and into June, the spring contributed less than 10% to the downstream discharge. From July to September the contribution of the spring increased to a maximum value of 60-80%. Contributions computed from mean daily water temperature matched discharge measurements more closely than estimates based on EC, which overestimated spring contribution. This overestimation was most obvious following rain events.

3.2.7 Hydrology summary

The techniques used to characterize the reach-scale hydrology suggest contrasting hydrology between the upper and lower subreaches. All evidence points to the upper subreach losing water to the subsurface. While the lower subreach appeared to be net losing water to the subsurface, EC survey and August 21 stream gauging measurements suggest localized inflow of subsurface water. Water chemistry analysis suggests that the inflow to the lower subreach was hyporheic exchange due to a relatively constant chemical signature along the subreach. The spring also appears to be comprised of hyporheic water because its chemical signature can be explained by a mixture of Skull Creek and Fishtrap Creek above Skull Creek water chemistry.
Figure 3.7: Downstream discharge contributions from spring discharge as estimated by EC, temperature and streamflow gauging measurements.
3.3 Temperature patterns

3.3.1 Stream temperature

Figure 3.8 presents stream temperature at the upstream and downstream boundaries of the full study reach and three subreach segments. Over the full study reach (length = 1457 m) instantaneous stream temperatures were similar between upstream and downstream sites. Downstream temperatures were sometimes slightly lower during daytime and slightly greater when nighttime temperatures dropped below 10 °C (Figure 3.8a). At the upper subreach (length = 613 m), downstream temperatures were typically 1-2.5 °C greater than upstream temperatures during midday, but nearly no different at night (Figure 3.8b). A middle subreach (length = 248 m), where the spring was located, experienced downstream decreases in stream temperature of up to 3 °C (Figure 3.8c). This decrease was mostly due to mixing with the spring water, which had a temperature of 8 °C in early July and warmed to a plateau of 10.2 °C during late July to September. When upstream temperatures of the middle subreach were below 10.2 °C, which occurred at night during mid and late August, downstream temperatures were slightly greater. The lower subreach (length = 596 m) exhibited almost no difference between upstream and downstream temperatures, although downstream temperatures were occasionally slightly less at midday.

Figures 3.9 to 3.12 present longitudinal stream temperature patterns on the four days for which energy budget calculations were made. Each day exhibited similar patterns of overall cooling during the early morning, warming until mid afternoon and subsequent cooling in the evening. The upper subreach experienced longitudinal warming during the day; however, the magnitude of warming differed for each date (e.g. up to 2-3 °C warming on July 29 and August 16, and up to 1-2 °C on August 9 and 21). The spring had an obvious cooling effect at nearly all times for each date, with the magnitude of the cooling effect increasing with increasing upstream temperatures. For a few periods, specifically 0400-0800 August 9, 0600-0800 August 16, and 0600-0800 August 21 the spring had a slight warming influence. The lower subreach had nearly uniform longitudinal temperature patterns for all
Figure 3.8: Upstream and downstream temperatures for the a) the entire reach (1457 m), b) the upper subreach (613 m), c) the mid subreach (248 m), d) the lower subreach (596 m). The mid subreach (c) also includes the spring temperature.
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### Table 3.3: Manual bed temperatures recorded at four locations (A,B,C,D) near the Lower Site meteorological station. Bed temperatures were measured at four depths (1, 5, 10 and 30 cm). The corresponding water temperature and measurement time are provided.

<table>
<thead>
<tr>
<th>Depth</th>
<th>0945 10 Aug</th>
<th>1145 16 Aug</th>
<th>1745 21 Aug</th>
<th>1145 7 Sept</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T&lt;sub&gt;W&lt;/sub&gt; = 10.8 °C</td>
<td>T&lt;sub&gt;W&lt;/sub&gt; = 12.0 °C</td>
<td>T&lt;sub&gt;W&lt;/sub&gt; = 11.3 °C</td>
<td>T&lt;sub&gt;W&lt;/sub&gt; = 10.7 °C</td>
</tr>
<tr>
<td>1 cm</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td></td>
<td>11.2</td>
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<td>11.8</td>
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3.3.2 Bed temperatures

Table 3.3 summarizes the manual bed temperature measurements recorded at four locations in the lower subreach. Three of the four sets of measurements were made in the morning and one measurement set was made in the late afternoon. There were small to no temperature gradients within the upper 10 cm at each location for the four days. The 30 cm bed temperature readings were typically lower (0.1-1.0 °C) than the shallower temperatures for the morning measurements and were slightly higher (0.1 °C) for the later afternoon measurements. Bed heat conduction computed from the bed temperature measurements represented a minor heat gain to the stream for the times sampled (Table 3.4).
Figure 3.9: Longitudinal variations in stream temperature for July 29. Profiles at two hour intervals for the a) morning cooling phase, b) warming phase and c) afternoon/evening cooling phase.
Figure 3.10: Longitudinal variations in stream temperature for August 9. Profiles at two hour intervals for the a) morning cooling phase, b) warming phase and c) afternoon/evening cooling phase.
Figure 3.11: Longitudinal variations in stream temperature for August 16. Profiles at two hour intervals for the a) morning cooling phase, b) warming phase and c) afternoon/evening cooling phase.
Figure 3.12: Longitudinal variations in stream temperature for August 21. Profiles at two hour intervals for the a) morning cooling phase, b) warming phase and c) afternoon/evening cooling phase.
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<table>
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<tr>
<th>Date</th>
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<th>Standard Error</th>
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<tr>
<td>1145 7 Sept</td>
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<td>0.0</td>
</tr>
</tbody>
</table>

Table 3.4: Calculated mean bed heat conduction and the standard deviation for the four bed temperature measurement locations.
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3.4 Riparian microclimate

Air temperature at the two riparian microclimate sites was generally similar during the study period (Figure 3.13). However, night temperatures were often slightly greater at the Upper Site and day temperatures were often slightly greater at the Lower Site. When comparing the Upper and Lower Site air temperatures to those recorded at the Open Site, the Open Site air temperature was typically 1-3 °C higher than the riparian conditions during the day and 2-5 °C higher during the night.

Vapour pressure at the two riparian microclimate sites was generally similar during the study period (Figure 3.14). The Open Site vapour pressure was typically 0.1-0.5 kPa less than measured at the riparian sites.

Both riparian microclimate sites experienced lower wind speed values than measured at the Open Site, with maximum wind speeds of 2 to 3 m/s (Figure 3.15). Even after accounting for movement of eddies through the stream valley by computing hourly averages, comparisons between the Upper and Lower Sites had a poor relationship.

3.5 Latent and sensible heat fluxes

Figures 3.16 and 3.17 present the calculated latent and sensible heat fluxes for the Lower Site and Upper Site stream and microclimate conditions. The latent and sensible heat fluxes were also calculated using the Upper or Lower Site stream temperature and the Open Site microclimate conditions. The latent heat flux, $Q_e$, was dominantly negative throughout the study period indicating evaporation was occurring. A diurnal pattern in $Q_e$ existed, with $Q_e$ nearing zero in the early morning and reaching a daily peak value in the late afternoon and early evening. Calculated $Q_e$ values using the Open Site conditions were often twice the magnitude of $Q_e$ values calculated using the Lower or Upper site conditions.

The sensible heat flux was dominantly positive throughout the study period. Similar diurnal pattern to $Q_e$, $Q_h$ neared zero or was slightly negative during the early morning and reached a maximum value in the late
Figure 3.13: Air temperature comparisons between the Open, Upper and Lower site meteorological stations. Day is defined as 6:00 to 18:00 and Night is defined as 18:01 to 5:59 the following morning.
Figure 3.14: Ten minute resolution vapour pressure comparisons between the Open, Upper and Lower site meteorological stations.
Figure 3.15: Averaged hourly wind speed comparisons between the Open, Upper and Lower site meteorological stations.
afternoon and early evening. Calculated $Q_h$ values using the Open Site conditions were often twice the magnitude of $Q_h$ values calculated using the Lower or Upper site conditions.

The sum of $Q_e$ and $Q_h$ was rarely greater than 50 Wm$^{-2}$ or less than -50 Wm$^{-2}$. Even using the Open Site conditions in the calculation of $Q_e$ and $Q_h$ resulted in a minimal net flux, as these terms tended to cancel out.
Figure 3.16: Estimated Lower Site latent ($Q_e$) and sensible ($Q_h$) heat fluxes. The Open Site fluxes were calculated using measured stream temperature at the Lower site but microclimate conditions measured at the Open Site meteorological station.
Figure 3.17: Estimated Upper Site latent ($Q_e$) and sensible ($Q_h$) heat fluxes. The Open Site fluxes were calculated using measured stream temperature at the Upper site but microclimate conditions measured at the Open Site meteorological station.
3.6 Net radiation

3.6.1 Estimation of missing solar radiation data

Due to pyranometer instrument failure at the Open Site meteorological station between August 18 to September 7, it was necessary to model incoming solar radiation to predict the missing values. Figure 3.18 presents the comparison of shortwave radiation measured at Fishtrap Creek (K\text{↓}_\text{FC}) and Mayson Lake (K\text{↓}_\text{ML}) for the period of July 13 to September 13, not including August 18 to September 7. The line of best fit is:

\[ K\text{↓}_\text{FC} = 2.01 + 1.02K\text{↓}_\text{ML} \tag{3.1} \]

which has an \( R^2 = 0.844 \) and a residual standard error of 109.1 Wm\(^{-2}\).

There is considerable scatter in the relationship, likely caused by variable cloud conditions between the two sites. Modelled Open Site shortwave radiation was most desired for August 21 (an energy budget analysis day), which appeared to be a partly cloudy day from the Mayson Lake data. Therefore, the Mayson Lake-Fishtrap Creek regression analysis was performed using both clear sky and cloudy conditions.
Figure 3.18: Relation between hourly incoming solar radiation at Mayson Lake and Fishtrap Creek for July 13 to September 13, not including August 18 to September 7. The least-squares regression line is shown in red.
3.6.2 Modelling solar radiation from hemispherical images

Using the record of shortwave radiation at the Open Site meteorological station each day was categorized as either clear sky or non-clear sky. Data from July 26 and 29, August 1 and 14 and September 10, 11, 13-15 were selected for clear sky analysis, while the remaining days were analyzed as non-clear sky days.

The results of the threshold analysis are shown in Figure 3.19. The optimum threshold value, when considering the root mean square error (RMSE) and mean bias error (MBE), at the Lower Site and Upper Site for both clear and non-clear sky days were ≈135 and ≈160, respectively. The lower optimum threshold value for the Lower Site was likely due to the hemispherical image being taken at that location at an earlier morning time period than at the Upper Site location. The Lower Site image brightness was lower than the Upper Site image. However, the analysis suggests that the incident solar radiation model was relatively insensitive to variations in threshold values. The similarity in error between clear and non-clear-sky days at the Lower Site suggests that the error associated with the Erbs et al. (1982) equation for partitioning diffuse and direct solar radiation, when applied at Fishtrat Creek, was consistent.

Figure 3.20 presents scatterplots of measured versus modelled incoming solar radiation for the Upper and Lower sites on clear and non-clear days using a GLA threshold of 160. There was little bias in the modelled incoming solar radiation calculations; however, the poor model performance for the Lower Site was likely due to incorrect alignment of the camera with the pyranometer in the field and/or improper registration of the hemispherical image. Because the evaluations used 10 min values, minor registration errors can have a large effect of model performance.

3.6.3 Measurement of albedo

The mean albedo of all measurements over the study period was 0.07 ($n = 39$). There was only a slight difference between computed albedo for the three water surface types (glides = 0.07, pools = 0.06 and riffles = 0.07).
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Figure 3.19: Threshold sensitivity analysis plots using measured and modelled shortwave radiation at the Upper and Lower Sites pyranometers, separated by clear and non-clear sky days. RMSE is the root mean square error and MBE is the mean bias error.
Figure 3.20: Modelled versus measured net shortwave radiation for the Lower and Upper sites on clear and non-clear sky days using an optimum GLA threshold of 160.
The mean albedo value is likely an overestimation due to the lack of low millivolt range on the voltmeter, which was particularly noticeable when measuring reflected short-wave radiation under cloudy conditions. Therefore, the albedo of the stream was assumed to be 0.05 (Oke, 1987).

3.6.4 Estimation of emissivities

The BFGS optimization method resulted in $\varepsilon_w$ and $\varepsilon_{vt}$ optimized values of 0.95 and 0.97, respectively. These values fall within the ranges reported in the literature for water surfaces and vegetation (Oke, 1987).

3.6.5 Evaluation of modelled net radiation

Results from the five sites where net radiation was modelled and measured are presented in Figures 3.21 and 3.22. For four of the five sites (Sites 2 to 5) the modelled net radiation closely matched the measured net radiation. At net radiation model evaluation site 1 the model performed well during the night, early morning and late evening; however, it performed poorly during midday. The poor performance was likely due to incorrect alignment of the camera with the net radiometer and/or improper registration of the hemispherical image. However, the daily radiation totals were approximately equal between measured and modelled values at this site.

3.6.6 Spatial variability in modelled net radiation

Figure 3.23 presents modelled net radiation for each of the hemispherical images taken at Fishtrap Creek for August 14th (a clear-sky day). During the day modelled net radiation was highly variable between the sampling sites with differences between individual sites being as large as 642 Wm$^{-2}$. At night the modelled net radiation closely agreed between sites due to similar sky view factors and stream and air temperatures. The RMSE and MBE for the single measurement of net radiation and the reach-scale modelled mean net radiation are 77 Wm$^{-2}$ and 14 Wm$^{-2}$, respectively. However, RMSE and MBE increases to 119 Wm$^{-2}$ and 25 Wm$^{-2}$, respectively, when considering only the daytime period.
Figure 3.21: Scatterplots and times series of modelled versus measured net radiation at net radiation model evaluation sites 1 through 3.
Figure 3.22: Scatterplots and times series of modelled versus measured net radiation at net radiation model evaluations sites 4 and 5.
Figure 3.23: Variations in 10 minute resolution modelled net radiation (gray lines) between 97 sampling sites (hemispherical images) distributed throughout the study reach for August 14. Modelled mean (red line) and measured net radiation at one site along the study reach (black line) are included for comparison.
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Table 3.5: Reach characteristics for the Lower Subreach (LS) and Upper Subreach (US) for the four energy budget analysis days. \( Q_{us} \) is the discharge measured at the upstream boundary of the subreach and \( Q_{ds} \) is the discharge measured at the downstream boundary of the subreach.

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>( Q_{us} ) (m$^3$s$^{-1}$)</th>
<th>( Q_{ds} ) (m$^3$s$^{-1}$)</th>
<th>Mean Width (m)</th>
<th>Mean Velocity (ms$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS</td>
<td>July 29</td>
<td>0.23</td>
<td>0.18</td>
<td>4.1</td>
<td>0.15</td>
</tr>
<tr>
<td>LS</td>
<td>August 9</td>
<td>0.20</td>
<td>0.17</td>
<td>3.6</td>
<td>0.14</td>
</tr>
<tr>
<td>LS</td>
<td>August 16</td>
<td>0.13</td>
<td>0.12</td>
<td>3.2</td>
<td>0.09</td>
</tr>
<tr>
<td>LS</td>
<td>August 21</td>
<td>0.16</td>
<td>0.18</td>
<td>3.4</td>
<td>0.14</td>
</tr>
<tr>
<td>US</td>
<td>August 9</td>
<td>0.16</td>
<td>0.14</td>
<td>5.2</td>
<td>0.12</td>
</tr>
<tr>
<td>US</td>
<td>August 21</td>
<td>0.12</td>
<td>0.09</td>
<td>4.5</td>
<td>0.10</td>
</tr>
</tbody>
</table>

3.7 Stream temperature modelling

The energy budget model was used to model stream temperature in the Lower Subreach, for which detailed field measurements to run the model were available on July 29 and August 9, 16 and 21. For two of the four days (August 9 and 21) detailed field measurements were also acquired for the Upper Subreach, which also allowed energy budget analysis of the full study reach for these two days.

Table 3.5 summarizes the field measurements of the upstream and downstream discharges, mean wetted widths and mean velocities for the Upper and Lower Subreachs. With the exception of August 21, all the measured stream characteristics decreased between July 29, August 9 and August 16, reflecting the overall trend of declining streamflow through the study period. On August 21 the Lower Subreach saw an increase in stream discharge, mean wetted width and mean velocity compared to August 16, likely due to the rain event which occurred on August 20.

3.7.1 Model evaluations

Figure 3.24 presents the August 9 and 21 energy budget model evaluations for the Upper Subreach. The predicted downstream temperature closely matched the observed stream temperature. There was slight model overprediction during mid-afternoon, which was more pronounced on August 21.
The modelled stream temperature underpredicted slightly during the night.

Figure 3.25 presents the energy budget model evaluations for the Lower Subreach. Model runs that did not include any groundwater inputs resulted in considerable overprediction during the daytime. The daytime overprediction of downstream temperatures by the energy budget model could not be explained solely by errors in estimated stream surface area or atmosphere-stream energy exchanges. Sensitivity analyses indicate that net radiation would have to be reduced by 75% to significantly improve the fit between modelled and measured values (Section 3.7.3). Including groundwater inputs, as suggested by the EC survey measurements, resulted in a close match between modelled and measured stream temperature. The temperature of groundwater inputs was set equal to the measured spring temperature (temperature site T(e)). The groundwater discharge was optimized for July 29
at 0.07 m$^3$s$^{-1}$ (i.e. $q_{in} = 1.17 \times 10^{-4}$ m$^3$s$^{-1}$m$^{-1}$). This value was applied to the other three days.

Figure 3.26 presents the energy budget model evaluations for the Full reach. This analysis incorporated the Upper Subreach model, the Lower Subreach model accounting for groundwater inputs, and the spring located at the midpoint of the reach. The downstream modelled stream temperatures over the 1500 m full reach closely matched the measured downstream temperatures on both August 9 and August 21, although slight model over-prediction occurred during mid-afternoon for both days.

Table 3.6 summarizes goodness-of-fit statistics for modelled stream temperatures. The model performed well in the Upper Subreach, with both the MBE and RMSE being of the same magnitude as or smaller than the nominal accuracy of the temperature loggers (0.02 °C). Nash-Sutcliffe model efficiencies equaled or exceeded 0.94 on both days. Similar performance was found for simulations of the Full Reach.

In the Lower Subreach, simulations that included groundwater discharge also performed well, with small MBE and RMSE, and Nash-Sutcliffe model efficiencies that exceeded 0.95. Not including groundwater discharge resulted in much poorer performance, with Nash-Sutcliffe efficiencies as low as 0.41.

3.7.2 Stream surface - atmosphere energy exchanges

Figure 3.27 presents the estimated stream surface - atmosphere energy exchanges. Net radiation was the dominant energy exchange while the turbulent energy fluxes were relatively minor terms. The net turbulent heat flux was often near zero. There were minor differences in the net radiation, latent and sensible heat fluxes between the Upper and Lower subreaches on August 9 and 21. These results suggest that differences in the thermal patterns between the Upper and Lower subreaches cannot be explained by the differences in energy exchanges occurring at the stream surface - atmosphere interface.
Figure 3.25: Energy budget model evaluations for the Lower Subreach. DS $T$ refers the downstream temperature and US $T$ refers to the upstream temperature.
Figure 3.26: Energy budget model evaluations for the Full Reach. DS refers to the downstream temperature and US refers to the upstream temperature.

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>Without gw term</th>
<th>MBE (°C)</th>
<th>RMSE (°C)</th>
<th>Nash-Sutcliffe</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS</td>
<td>July 29</td>
<td>without gw term</td>
<td>0.50</td>
<td>0.67</td>
<td>0.65</td>
</tr>
<tr>
<td>LS</td>
<td>August 9</td>
<td>without gw term</td>
<td>-0.10</td>
<td>0.17</td>
<td>0.98</td>
</tr>
<tr>
<td>LS</td>
<td>August 16</td>
<td>without gw term</td>
<td>0.28</td>
<td>0.42</td>
<td>0.75</td>
</tr>
<tr>
<td>LS</td>
<td>August 16</td>
<td>with gw term</td>
<td>0.06</td>
<td>0.10</td>
<td>0.98</td>
</tr>
<tr>
<td>LS</td>
<td>August 21</td>
<td>without gw term</td>
<td>0.48</td>
<td>0.63</td>
<td>0.50</td>
</tr>
<tr>
<td>LS</td>
<td>August 21</td>
<td>with gw term</td>
<td>0.01</td>
<td>0.11</td>
<td>0.99</td>
</tr>
<tr>
<td>LS</td>
<td>April 21</td>
<td>without gw term</td>
<td>0.32</td>
<td>0.40</td>
<td>0.41</td>
</tr>
<tr>
<td>LS</td>
<td>April 21</td>
<td>with gw term</td>
<td>0.07</td>
<td>0.11</td>
<td>0.95</td>
</tr>
<tr>
<td>US</td>
<td>August 9</td>
<td></td>
<td>-0.08</td>
<td>0.19</td>
<td>0.98</td>
</tr>
<tr>
<td>US</td>
<td>August 21</td>
<td></td>
<td>0.01</td>
<td>0.22</td>
<td>0.94</td>
</tr>
<tr>
<td>Full Reach</td>
<td>August 9</td>
<td></td>
<td>0.02</td>
<td>0.13</td>
<td>0.98</td>
</tr>
<tr>
<td>Full Reach</td>
<td>August 21</td>
<td></td>
<td>0.06</td>
<td>0.13</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Table 3.6: Goodness-of-fit statistics for modelled stream temperatures. The Lower Subreach models were run twice, once without the groundwater term and once with the groundwater term. LS and US are the Lower Subreach and Upper Subreach, respectively. MBE and RMSE are the mean bias error and root mean square error, respectively.
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Figure 3.27: Estimated stream surface - atmosphere energy exchanges for the four Lower Subreach simulation days and the two Upper Subreach simulation days.
3.7.3 Sensitivity analysis

Figures 3.28 and 3.29 present sensitivity analysis results for the Full Reach for August 9 and 21. Increasing the reach mean channel width by 1 m, and thereby increasing the surface area for net radiation, latent and sensible heat fluxes to occur, resulted in less than a 1 °C increase in stream temperature. Decreasing the reach mean channel width by 1 m resulted in less than a 1 °C decrease in stream temperature. Increasing and decreasing net radiation by 50% resulted in a change in predicted stream temperature during the daytime, but had little effect on nighttime stream temperature. Altering the latent and sensible heat fluxes had little effect on stream temperature. Decreasing the discharge of the spring resulted in increased daytime stream temperatures and increasing the discharge of the spring resulted in decreased daytime stream temperatures. However, changes to the spring discharge had little influence on nighttime temperatures. Altering the spring temperature resulted in stream temperature changes throughout the day, with greater increases at night. Increasing the discharge of the diffuse groundwater input term in the Lower subreach resulted in a decrease in stream temperature throughout the day. Decreasing the groundwater input term resulted in an increase in stream temperature during the daytime and little change during the night.
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Figure 3.28: Sensitivity analysis for the full reach stream energy budget model for August 9.
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Figure 3.29: Sensitivity analysis for the full reach stream energy budget model for August 21.
3.8 Virtual experiments

In this section the results of two virtual experiments examining the role of stream-subsurface interactions and canopy cover conditions, specifically standing dead riparian vegetation, on stream temperature are presented.

3.8.1 Stream-subsurface interactions

Figure 3.30 presents the modelling results of the energy budget analysis for the full reach on August 9. The ‘without spring’ scenario removes the spring and assumes the longitudinal discharge along the entire reach was constant. This scenario results in an overprediction of stream temperature of up to 1 °C during the daytime and a small underprediction during the nighttime. The ‘without spring and LS SW-GW’ scenario takes the previous scenario, but also removes the surface water and groundwater interactions to the Lower Subreach. This scenario results in an overprediction of stream temperature of up to 2.5 °C during the daytime and up to 0.7 °C underprediction during the night.

3.8.2 Canopy cover

Figure 3.31 presents the modelled net radiation associated with the three canopy cover scenarios: current (post-disturbance) conditions, terrain only with the trees removed, and simulated pre-disturbance (Jamieson Creek) conditions. The net radiation associated with the current conditions (dead defoliated standing riparian vegetation) was about one third less and twice the net radiation associated with the trees removed scenario and the pre-disturbance scenario, respectively, during midday. During the night all three scenarios have relatively similar net radiation, with greatest losses associated with the trees removed scenario, followed by the current conditions and pre-disturbance scenario.

Figure 3.32 isolates the net shortwave radiation and incoming longwave radiation components of the modelled net radiation associated with the three canopy cover scenarios. The differences in modelled net radiation between
Figure 3.30: Full reach stream energy budget model for August 9. The ‘With SW-GW’ scenario accounted for the dynamic nature of the stream discharge along the study reach. The ‘Without spring’ scenario assumed a constant stream discharge (0.16 m$^3$s$^{-1}$) and did not account for the spring inputs, but did account for the Lower Subreach groundwater inputs. The ‘Without spring and LS SW-GW interactions’ was similar to the ‘Without spring’ scenario but with the effect of the groundwater inputs into the Lower Subreach not included.
the three scenarios are explained primarily by the differences in shortwave radiation. The differences in canopy cover have only a small influence on the longwave component of net radiation.

Figure 3.33 presents the stream energy budget model results for August 9 and 21 incorporating the three canopy cover scenarios and their associated net radiation dynamics. The terrain only scenario resulted in daytime stream temperatures up to 1.5 °C greater than the post-disturbance current conditions. The simulated pre-disturbance scenario resulted in daytime stream temperatures up to 1-1.5 °C less than the post-disturbance current conditions.
Figure 3.32: Modelled net shortwave radiation and incoming longwave radiation under three canopy cover scenarios.
Figure 3.33: Modelled downstream stream temperature over the full reach under three canopy cover scenarios.
Chapter 4

Discussion

This chapter discusses the significance of the results presented in Chapter 3 and is focused on the research questions outlined in Chapter 1.

4.1 Characterizing reach-scale hydrology

Results from this study suggest that characterizing reach scale hydrology by comparing measured upstream and downstream discharge measurements may be insufficient to understand both the stream-subsurface interactions and the stream thermal regime. At the Fishtrap Creek full study reach scale, comparing upstream and downstream discharge measurements would have led to the conclusion that the reach was either neutral or slightly gaining. The more detailed spatial measurements showed that the reach scale hydrology had a more complex nature. Quantifying the role of the spring on the reach scale hydrology was relatively easy as it was visible and easily measured. However, the stream-subsurface interactions occurring in the Lower Subreach were more difficult to quantify despite its significant influence on stream temperatures, as suggested by the energy budget analysis.

The use of EC and water chemistry surveys helped to assess the hydrological behaviour of Fishtrap Creek for the Full reach and Upper and Lower subreaches. Unfortunately, due to the coarse bed and riparian zone substrate material at Fishtrap Creek, the use of wells and piezometers to assist in characterizing the stream-subsurface interactions was not possible. The water chemistry analysis suggests that subsurface discharge into the lower reach, including the spring, is likely hyporheic water. This research and the work of Story et al. (2003) highlight the need for additional field measurements beyond measuring upstream and downstream discharges to properly
characterize reach-scale hydrology for stream temperature purposes.

4.2 Energy budget considerations

4.2.1 Latent and sensible heat fluxes

Properly characterizing the riparian microclimate of a stream is important for energy budget calculations of the latent and sensible heat fluxes. The two above-stream meteorological stations at Fishtrap Creek were located approximately 900 m from each other. However, measurements of air temperature and humidity showed strong agreement between stations. In previous energy budget studies, where reach lengths were often less than 200 m, a single detailed microclimate monitoring site was typically used to represent conditions over the full study reach (e.g. Story et al. 2003; Hannah et al. 2008). The results from Fishtrap Creek suggest that for air temperature and humidity this assumption is justified. However, wind speed was highly variable between the stream meteorological stations (Figure 3.15) and therefore may not be representative of the entire study reach. This variability in wind speed was not a significant issue when used in the calculations of the turbulent energy fluxes at Fishtrap Creek because these fluxes were relatively minor stream temperature controls. For autumn and winter or much larger, less sheltered rivers or sites with greater canopy cover and/or less groundwater influence than experienced at Fishtrap Creek, the turbulent fluxes may become relatively more important to the stream heat budget (e.g. Hannah et al. 2008). However, with greater canopy cover the stream microclimate will likely be more sheltered, resulting in low wind speeds and lower estimated turbulent fluxes (Story et al., 2003).

The climate characterized by the Open site meteorological station differed from the climates characterized by the two-above stream meteorological stations. The open site was typically warmer, windier and less humid than the stream sites. Johnson (2003) argued that the use of remote climate station data for reach-scale energy budget model calculations (e.g. Sinokrot and Stefan 1993) may not be justified. Results from this study support
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this argument. However, the turbulent fluxes were relatively insignificant stream temperature controls at Fishtrap Creek, which is consistent with most previous energy budget studies conducted in forested environments (e.g. Brown 1969; Johnson 2004; Moore et al. 2005a). Therefore, the microclimate variability that does exist between the upland and stream sites was not significant enough to cause large errors in energy budget calculations. A further mitigating factor in the use of upland meteorological data in this study is that the sensible and latent heat fluxes were dominantly of opposite signs and tended to cancel. This cancelling of terms may not be the case for other streams, particularly larger, less sheltered streams. Therefore, heat budget calculations based on remote climate data should be treated with caution, especially when \( Q_h \) and \( Q_e \) have the same sign.

4.2.2 Net radiation

Net radiation was found to be the principal driver of stream warming in the upper subreach. This result is consistent with most other energy budget studies focused on summer. In the lower subreach, net radiation was often a significant source of energy into the stream during the day. However, this net radiation input did not translate into stream warming as occurred at the upper subreach, due to the moderating effect of subsurface discharge.

Quantifying riparian vegetation canopy structure and its influence on reach-scale radiation exchange has been a challenge in many of the previous energy budget studies due in part to instrument availability (Brown, 1969; Webb and Zhang, 1997). Following Moore et al. (2005b) and Guenther (2007), this study used hemispherical images to calculate canopy gap fractions for use in a deterministic net radiation model. The model predicted net radiation accurately when evaluated against spot measurements of net radiation. Setting the threshold for converting the photographs to binary images is likely the model component with the greatest level of subjectivity. Appropriate threshold values were relatively easy to determine for the vegetation structure at Fishtrap Creek because of the lack of foliage, which resulted in a stark contrast between sky and the defoliated vegetation in
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the hemispherical images. This stark difference in sky and vegetation was not present for Guenther (2007), who experienced difficulties in differentiating between sky and vegetation under a riparian zone dominated by living coniferous trees. The threshold sensitivity analysis conducted in this study suggests that a relatively wide range of threshold values can be appropriate when dealing with standing dead defoliated riparian vegetation.

It was possible to evaluate the two primary components (net shortwave and net longwave radiation) of the net radiation model in this study using the field instrumentation installed at Fishtrap Creek. The net radiation model could have been improved had the diffuse component of shortwave radiation and the longwave radiation emitted by the atmosphere been measured directly at the study site. Instead, the model relied on standard empirical equations to calculate these terms, which introduces a level of uncertainty.

Black et al. (1991) showed that $L_{\downarrow}$ beneath a Douglas-fir canopy on Vancouver Island could be accurately approximated by assuming that the temperature of the vegetation was equal to air temperature. It is possible that this assumption to calculate longwave radiation was not met at Fishtrap Creek. While some riparian trees have shed their bark, resulting in the lighter wood being exposed, many trees still have their burnt, blackened bark and the sun-facing sides could heat up during the daytime.

Comparisons of the modelled net radiation between the nearly 100 sampling sites where hemispherical images were taken showed that daytime net radiation was highly variable throughout the study reach. One measurement of net radiation thus does not properly represent the reach-average net radiation flux. Spatial variability may be less of an issue for energy budget studies conducted on streams with little to no riparian vegetation and where terrain and bank shading are not significant (e.g. Hannah et al. 2004; Cozzetto et al. 2006). However, it is likely significant for forest streams (e.g. Brown 1969; Story et al. 2003; Hannah et al. 2008) due to the spatial variability in riparian vegetation structure. Capturing the spatial variability in net radiation is therefore critical due to the relative importance of net radiation as a control on stream temperature.
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A number of different approaches have been used in the literature to overcome the challenge of quantifying spatial variability in riparian vegetation canopy structure (Davies-Colley and Rutherford, 2005). The use of hemispherical images (as in this study) has been cited as being an expensive and time consuming approach to quantifying stream shade (Kelley and Krueger, 2005). However, the technological expense has decreased significantly in recent years and the time needed to capture the images in the field is small (100 images were taken over a 6 hour period in this study). A relatively small sample size of hemispherical images is needed to properly represent sites compared to other techniques (Kelley and Krueger, 2005). However, processing the hemispherical images is time consuming. Future work should aim to automate hemispherical image processing as well as reduce the subjectivity involved in this step.

4.2.3 Surface-subsurface water interactions

Hyporheic exchange, which has been recognized as a potentially important control on stream temperature, was not included in the Upper Subreach energy budget model. Energy budget model calculations for the Upper Subreach still predicted stream temperatures correctly, suggesting either the heat flux associated with hyporheic exchange was a negligible control on stream temperature or the energy budget model output was incorrect and nonunique (Oreskes et al., 1994). The physical characteristics of the Upper Subreach suggest that the former condition is true. The Upper Subreach had nearly constant longitudinal EC values measured during field surveys, which suggested no inputs of dissimilar water, either from groundwater or from hyporheic exchange. The Upper Subreach had an uncomplicated channel morphology (i.e. there was little channel sinuosity and no step-pool formations), which would make it less conducive to significant hyporheic exchange, such as occurs in highly sinuous and steep channels with step-pool or riffle-pool morphologies (Kasahara and Wondzell, 2003). There was small overprediction of stream temperature during the day and underprediction during the night for the Upper Subreach, which is consistent with the typical influence
of hyporheic exchange during the summer (Moore et al., 2005a). However, this influence was apparently sufficiently small that it did not cause problems in closing the energy budget for the Upper Subreach.

Closing the energy budget for the Lower Subreach was problematic. Including the same model components that were used for the Upper Subreach resulted in considerable stream temperature overprediction during the day. When the groundwater/hyporheic term was added to the model, set equal to the temperature of the spring and at a constant discharge, the predicted stream temperatures closely matched observed temperatures. EC surveys and stream discharge measurements made after the rain event on August 20 suggest that there may be shallow groundwater discharging into the Lower Subreach. The magnitude and temperature of such discharge were not measurable; however, the chemistry analysis suggests that the discharge is hyporheic exchange because the water is chemically similar to the stream water. Conceptually, the addition of the groundwater/hyporheic term is physically sound as the term includes the spatial patterns of recharge and discharge components of hyporheic exchange. Also, the lower subreach has a relatively more complex channel morphology than the upper subreach (i.e. there was greater channel sinuosity and more log jams), which would likely increase hyporheic exchange (Kasahara and Wondzell, 2003).

The full reach energy budget calculations, accounting for the Lower Subreach groundwater/hyporheic inputs and the spring discharges, predicted stream temperatures that closely matched the observed temperatures. This strong agreement between modelled and observed stream temperatures suggests that the spatiotemporal variability in energy exchange processes was well represented. Accounting for the spring discharge with a simple mixing equation was sufficient to capture its effect on stream temperature.

### 4.2.4 Bed heat conduction

Bed heat conduction was not included in the energy budget model used in this study. The Upper Subreach was a losing reach, which would reduce the thermal gradient into the bed and thus decrease the bed heat conduction flux.
(Moore et al., 2005b). There was small overprediction of stream temperature during the day and underprediction during the night for the Upper Subreach, which is consistent with the typical influence of bed heat conduction (and hyporheic exchange) during the summer (Moore et al., 2005a). However, this influence was apparently sufficiently small that it did not cause problems in closing the energy budget for the Upper Subreach.

As discussed in the previous section regarding stream-subsurface interactions, including the same model components for the Lower Subreach that were used for the Upper Subreach resulted in considerable stream temperature overprediction during the day. Spot estimates of bed heat conduction at the Lower Subreach suggest this term is negligible and cannot account for the difference between modelled and measured stream temperatures. However, the spot measurements of bed heat conduction may not be representative of the entire subreach as bed thermal gradients can exhibit great spatial variability (Story et al., 2003; Moore et al., 2005b). Regardless, to close the lower subreach energy budget would require bed heat conduction rates of opposite sign and larger than spot estimates (e.g. -300 Wm$^2$ versus 2.6 Wm$^2$, for August 21). The groundwater/hyporheic term that was added to the model to account for the lower subreach cooling likely includes the influence of bed heat conduction; however, isolating its contribution was not possible.

4.3 Implications for stream temperature research

The contrast between thermal regimes of the Upper Subreach and Lower Subreach emphasizes a number of key points from this study. Both subreaches experienced similar energy exchanges at the air/water interface. Both subreaches appeared to be losing reaches based on differences in upstream and downstream discharge measurements. However, the temperature patterns of the subreaches differed considerably. The Upper Subreach experienced downstream warming of up to 2-3 °C during the daytime, while the Lower Subreach rarely experienced downstream warming greater than 0.5 °C. EC surveys and the energy budget modelling suggested that surface-
subsurface water interactions in the Lower Subreach were the primary reasons for the differences in stream temperature patterns between the two subreaches.

Caissie (2006) argued that stream energy exchanges mainly occur at the air/water interface and only a small amount occurs at the bed/water interface. Caissie (2006) cited the study by Evans et al. (1998) specifically to support this claim. The results of the study at Fishtrap Creek suggest that hyporheic or groundwater discharge can have a significant control on stream temperature. A potential reason why Evans et al. (1998) and other studies (e.g. Webb and Zhang 1997; Hannah et al. 2008) have consistently concluded that the energy exchanges at the air/water interface are much more important than fluxes at the bed/water interface may be the relatively short reaches studied (less than 40 m lengths). Studying relative short reaches emphasizes the role of vertical fluxes. At Fishtrap Creek the same conclusion would be made if only the Upper Subreach was examined. However, when moving to the full reach scale the importance of advection due to groundwater discharge or hyporheic exchange on stream temperature becomes clear. This research highlights that stream-subsurface interactions play an important role in determining stream temperature patterns when moving from essentially the point scale (i.e. < 40 m reach length) to the reach scale (i.e. > 200 m reach length).

It is unlikely that the importance of the stream-subsurface interactions on stream temperature found at Fishtrap Creek is unique to this site. Other researchers have noted the importance of stream-subsurface interactions on stream temperature but were unable to explicitly quantify these interactions within an energy budget analysis (Webb and Zhang, 1997; Hannah et al., 2008). Story et al. (2003) quantified stream-subsurface interactions using tracer and hydrometric measurements. They found that groundwater discharge and hyporheic exchange were significant drivers of downstream cooling observed at their site. The longitudinal discharge patterns at their site were similar to Fishtrap Creek (upper losing reach, lower gaining reach), despite substantial differences in stream size. With improved understanding of stream-subsurface interactions and energy budget analyses conducted on
longer stream reaches, it is likely that the importance of stream-subsurface interactions on stream thermal regimes will be further realized.

The sensitivity analysis suggests that the Fishtrap Creek thermal regime is highly sensitive to changes not only in the magnitude of the stream-subsurface interactions but also the temperature of the advective inputs. Process-based modelling of long term stream temperature response to climate change has focused on changes to the energy exchanges at the air/water interface (Gooseff et al., 2005). Climate change could have a considerable effect on groundwater-surface water interactions, particularly by changing the timing and magnitude of spring snowmelt and subsequently the timing and magnitude of aquifer recharge and discharge (Scibek et al., 2007). Additionally, groundwater temperature is usually related to air temperature and would be expected to increase under climate warming. No research has examined the long term effect of groundwater-stream water interactions on stream temperature regimes. The modelling results from this study, which suggests that stream temperatures are sensitive to changes in groundwater-stream water interactions and subsurface water temperatures, coupled with the work by Scibek et al. (2007) suggest that the stream thermal response to climate change could be considerable.

### 4.4 Standing dead riparian vegetation

The primary finding from the canopy cover virtual experiment was that standing dead defoliated riparian vegetation does reduce the amount of net radiation reaching the stream during the day compared to complete removal of the vegetation. While the current post-disturbance scenario produced slightly higher longwave than calculated for the case of complete canopy removal, the decrease in incoming solar radiation is quantitatively more important. While this reduction was considerable, approximately one-third more net radiation reached the stream surface during midday under the post-disturbance conditions than under the simulated pre-disturbance conditions.

There were three primary assumptions associated with translating the canopy cover scenarios into stream temperatures using the energy budget
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model. The first assumption was that the latent and sensible heat fluxes were not affected by changes in riparian vegetation structure. The conditions controlling the latent and sensible heat fluxes (e.g. wind speed, air temperature and humidity) were likely affected by the change from pre-disturbance to post-disturbance riparian vegetation structure. As the sensitivity analysis suggests, latent and sensible heat fluxes were a negligible control on stream temperature. These fluxes would likely be even smaller under predisturbance conditions due to reduced wind speeds. Therefore, assuming these fluxes were unchanged for the different canopy cover scenarios does not likely affect the corresponding stream temperature responses. The second assumption was that the hydrological processes at Fischtrap Creek were not affected by changes in riparian vegetation structure. Changes in the evapotranspiration rates occurring in the riparian zone or earlier snowmelt occurrence due to the death of the trees may affect the groundwater table level and subsequently the stream-subsurface interactions. The third assumption was that the stream temperatures upstream of the study reach were not influenced by changes in riparian vegetation structure. This assumption was likely violated due to the wildfire extending upstream of the study reach.

Using Jamieson Creek to simulate the pre-disturbance riparian vegetation structure at Fischtrap Creek involved assumptions and advantages over typical approaches for detecting disturbance response. In addition to the assumptions mentioned above, it was assumed that the riparian vegetation type and structure were similar to Fischtrap Creek prior to the disturbance. While the most robust approach for detecting disturbance responses is the Before-After/Control-Impact (BACI) design (Moore and Wondzell, 2005), the unpredictable nature of wildfire makes using this approach difficult. Further, finding a control stream with sufficiently similar channel aspect, stream width and local topography can be difficult. A key advantage of using hemispherical images from Jamieson Creek to simulate pre-disturbance conditions at Fischtrap Creek was the ability to correct for channel aspect, stream width and local topography. Natural variability between streams, in terms of stream-subsurface interactions, and confounding climatic variability as-
associated with before-after studies, were thus not an issue when using this technique.

Leach and Moore (in press) found a statistically detectable increase in summer stream temperature of approximately 2 °C following the wildfire disturbance at Fishtrap Creek. This increase is greater than the increase suggested by the virtual experiment (1-1.5 °C). However, as mentioned, modelled pre-disturbance stream temperature used measured upstream temperature as input to the model. This measured upstream temperature has likely increased due to the wildfire disturbance. This confounding upstream temperature increase may account for the discrepancy between the modelled summer stream temperature increase from the virtual experiment and the statistically detected increase. This modelling exercise strongly suggests that the observed stream temperature increase at Fishtrap Creek was due to an increase in solar radiation caused by defoliation of the riparian vegetation.
Chapter 5

Conclusion

In the first section of this chapter the key findings, which address the research questions posed in Section 1.3, are given. In the final section directions for future research are discussed.

5.1 Key findings

Within-reach variations in air temperature and vapour pressure were minimal throughout the study period, although differences of up to 5 °C and 0.5 kPa did occur, respectively. Within-reach wind speed was highly variable, as suggested by the poor correlation in measured wind speed between the two stream meteorological stations. The net radiation model illustrated the considerable spatial variability in net radiation along the study reach, with instantaneous differences of up to 700 Wm$^{-2}$ between sites. These findings suggest that single measurements of riparian air temperature and humidity adequately represent reach-scale variability. However, wind speed and net radiation are not adequately represented by single measurements. The finding that net radiation is not adequately represented by a single measurement is of great import, because net radiation is often cited as the most important stream temperature control (Brown, 1969; Evans et al., 1998; Webb and Zhang, 1999; Hannah et al., 2008).

Using upland meteorological data, measured approximately 200 m from Fishtrap Creek, to estimate the turbulent heat fluxes resulted in calculated flux magnitudes often twice as great as estimated using the above-stream meteorological data. The directions of the sensible and latent heat fluxes were often opposite, resulting in the terms cancelling. As well, the turbulent heat fluxes were relatively minor stream temperature controls at Fishtrap
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Creek. Therefore, the discrepancy between estimates was not an issue at Fishtrap Creek. However, the use of upland meteorological data to estimate the turbulent heat fluxes could become an issue for larger, less sheltered streams, where the turbulent heat fluxes might be a significant control on stream temperature.

Consistent with Story et al. (2003), reach-scale surface-subsurface water interactions were a significant control on the stream thermal regime. It was necessary to characterize the spatial complexity of surface-subsurface interactions to adequately model stream temperature. The Upper Subreach thermal regime was dominated by the vertical energy fluxes occurring at the air/water interface. The Lower Subreach thermal regime was dominated by groundwater and/or hyporheic exchange, despite similar magnitudes in energy exchanges at the air/water interface to the Upper Subreach. Assuming a constant discharge throughout the reach, as suggested by the full-reach upstream and downstream discharge measurements, resulted in up to a 2 °C overprediction of stream temperature during the day and a 0.5 °C underprediction at night. Despite gaps in understanding the complex hydrology at Fishtrap Creek, this research highlights the significant influence surface-subsurface water interactions can have on stream thermal regimes.

This study has demonstrated that standing dead trees do reduce daytime net radiation and stream warming relative to what would occur with a total loss of riparian vegetation. However, standing dead trees increase daytime net radiation and stream warming relative to pre-disturbance, foliated canopy conditions. Although net longwave radiation losses increase with the progressive reduction in canopy cover, the net radiation dynamics and stream temperature response were dominated by increases in solar radiation reaching the stream. This study strongly suggests that the post-fire warming detected by Leach and Moore (in press) is due to increased solar radiation reaching the stream surface. The management implications resulting from the canopy cover virtual experiment are that if mitigating stream temperature warming is an important objective, leaving the dead standing riparian trees intact can contribute to this objective.
5.2 Future research

This study has highlighted the importance of understanding within-reach energy exchange variability, particularly net radiation and hydrological processes, in controlling stream temperature at the reach-scale. Future research should ultimately move to the stream network scale to further assess spatiotemporal variability in stream temperature controls and to understand how these various processes interact at the stream network scale.

Understanding subsurface hydrology remains a primary challenge for researchers. This study highlights the importance of the spatiotemporal subsurface processes in governing stream temperature. Therefore, continued advancement in the conceptualization and understanding of stream-subsurface interactions will hold benefits not only for stream temperature research, but a wide range of topics associated with subsurface hydrology.

Process-based modelling of long-term stream temperature response to climate change has focused on changes to the energy exchanges at the air-water interface (Gooseff et al., 2005). However, this study and work by Story et al. (2003) highlight the influence that energy exchange processes associated with groundwater and hyporheic exchange can have on the stream thermal regime. Climate change could have a considerable effect on groundwater-surface water interactions, particularly by changing the timing and magnitude of spring snowmelt and subsequently changing the timing and magnitude of aquifer recharge and discharge (Scibek et al., 2007). Future research should examine how groundwater-stream water interactions may change under future climatic conditions, and the consequences for stream temperature dynamics.

This study has effectively characterized the summer net radiation and stream temperature dynamics for a stream four years after a wildfire disturbance. Continued energy budget research as the riparian zone continues to respond, and ultimately recovers, from the disturbance would address a number of key questions. Phillips (2007) has documented significant channel response to the wildfire disturbance, which is expected to continue. In a retrospective comparative study, Dunham et al. (2007) found that streams
which were burned and exhibited significant channel reorganization were more likely to have summer stream temperatures exceed 20 °C than burned streams which exhibited little channel reorganization. Therefore, an important question is how will the channel morphological response influence stream temperature and how will the riparian vegetation regrowth influence net radiation?

This research has contributed to an increasing body of knowledge regarding the dynamics of and controls on stream temperature. However, further research is required to connect this stream temperature understanding to its influence on aquatic ecological processes. By making this connection, it will be possible to address questions about the broader significance of stream temperature.
References


References


